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Exploring Metacognition, Student-Generated Rubrics and the Development of Scientific Reasoning and Process Skills in Grade 11 Science Classrooms

by

Jennifer MacLean ©

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Master of Education

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Abstract

The main focus of this research is to examine the use of student-generated rubrics in science classrooms and to determine the extent of student ownership of the learning process. Subjects in this study were grade eleven chemistry and biology students. Over the course of this action research, student experimental work, student learning logs, student self and peer assessments, and individual and group collaborative rubrics were collected. Extensive analysis of interview transcripts from student and teacher conversations were compiled, and an ongoing teacher log and extensive field notes were kept throughout the process.

Although classroom context is an important consideration, it was found that when the rubric generation process is limited to a set number of criteria and uses clear standards depicting action, it can be a vehicle for helping motivated students internalise standards of quality. This allows students to become more metacognitively aware of themselves as learners of science.

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Chapter I: Introduction

Context of the Study

For the last ten years I have been steadily working towards the incorporation of formative assessment practices within my secondary science classes. The underlying philosophy behind the utilization of these strategies is to teach for meaningful understanding, ownership of learning and applicability, as opposed to content. This research focus has been narrowed to a particular aspect of learning and how it can be applied to the development of science process skills. My initial interest in this pedagogical approach came about through conversations with a colleague who currently teaches high school English classes. The incorporation of student-generated rubrics to help develop writing process skills is an encouraged practice in many high school humanities courses. Language skill development can also play a role in science learning as it can encourage the learner to express and consolidate acquired knowledge (Jones, 1997).

Students involved in laboratory science often encounter difficulties co-ordinating scientific theory with evidence. If students are encouraged to focus merely on data gathering and procedural methods, scientific meaning through data analysis, scientific reasoning and application is often lost (Zohar, 1998). The ability to communicate science concepts through writing about authentic laboratory experiences is an ongoing skill that should be facilitated in a developmental context within science classrooms. For science to become more than just fact gathering it is necessary that the language of science be used in a context where students are encouraged to share and compare their interpretations and attempt to produce agreement about their perceptions (Sutton, 1994). In this manner, science curricula can be approached through building coherent and mutually reinforcing knowledge structures that encourage overall pattern forming and connections rather than learning isolated topics. It occurred to me that a process similar to the one being used in my colleague's English classroom to develop essay writing skills could also be incorporated into a science classroom with the aim of developing both scientific literacy and process skills for laboratory work over the long term.

The type of science discipline chosen and the particular laboratory experiments performed are important in terms of gathering data for the research process, but it is my belief that the pedagogical approach and philosophical framework underpinning this study should apply across all science disciplines. The action research initially began with two classes of eleventh grade chemistry, containing 35 students each, at one high school over a period of five months. Upon moving to another high school, I waited for another five months in order to gain the appropriate degree of entry with my administration, my colleagues, and the students. The research cycle was further reflected upon and developed for an eleventh grade biology classroom of 24 students. Although the majority of my findings relate to the biology classroom, I will also include research from the initial chemistry classrooms to illustrate the inter-disciplinary nature of the study and the importance of context.

At the beginning of the semester, I discussed with my students a generalized plan of action in relation to performing scientific inquiry and generating scientific process skills in the classroom. I asked students to present their experimental designs after performing an initial open-ended experiment. After analysing the various designs as a group, students and teacher then participated in generating assessment criteria for laboratory write-ups. In the role of teacher, I chose the experiments to be performed based on the Biology 20 and Chemistry 20 curricula, and the generalized rubric assessment criteria (scientific methodology, science content, data representation, hypothetico-deductive reasoning skills, and communication). The students (with myself as facilitator) collaboratively decided upon the specific standards within the rubric as individuals, in small groups and as an entire class. The rubric changed over time, as a result of peer discussion and self-reflection on its use. The assessment process in general was modified with the feedback received by the students and with respect to their comfort levels in having their work assessed by others. Students were asked to write about their critical analysis skills and comment on areas that needed improvement. As well, they were asked to reflect on the evaluation process itself, their role as evaluators, and their own evaluated laboratory write-ups in their ongoing learning logs. Comments made by the students determined the manner in which the assessment strategies were incorporated into the study.

Purpose of the Study

The main focus of this research is to examine the use of student-generated rubrics in the development of science process skills. My research is based on the belief that student assessment in science can be improved by employing strategies that enable students to become more actively involved in their own assessment. This study involved myself as reflective practitioner in collaboration with students in determining assessment practice. The process itself is ongoing and focuses on providing students with an authentic science experience while developing skills that can be further applied to novel situations, in keeping with a science-technology-science, or STS, approach to science education.

Significance of the Study

Science teachers often find themselves trying to implement a curriculum that stresses an STS approach with standardized assessment practices that demand one right answer. Thus, a discordance can exist between the goals for instruction and student assessment. An STS approach to curriculum requires educators to provide social contexts for the interaction of science and technology, and to acknowledge the lived experiences of students as relevant to their understanding of science. Alberta Learning's "Vision for High School Science Programs" states:

> Students will be expected to show an appreciation for the roles of science and technology in understanding nature and maintaining a lifelong interest in science. They will possess positive attitudes toward and enthusiasm for science. (1991, p.1)

In order to reach these goals, it is necessary for educators to provide the appropriate context for the learning of science. Alberta Learning's vision statement goes on to state that:

> The learning opportunities will be made meaningful by providing concrete experiences that students relate to their world. (1991, p.1)

Educators are being encouraged to relate what is being learned in the classroom to life experiences.

The reality of the typical science classroom does not always match either the curricular intent or reflect the nature of science as it is currently recognized by scientists themselves. Evaluation strategies which are grounded in the technocratic principles of standardized assessment place teachers as all-knowing experts who dole out their knowledge to students in unconnected bits and pieces. The control of learning remains in the hands of the educator whose belief in objective and one-right-answer science is demonstrated in the carrying out of recipe book laboratory work by students. Teacher and students alike place value on what the students learn rather than on how they are learning it.

Much of the educational research in science pedagogy is tied to particular subjects, grade levels, and science concepts. When examined as a whole, they tend to reinforce the view that secondary school science is learned as a series of unconnected small topics (Driver, 1991). There is a need for studies that examine the effects of science pedagogies which link science phenomena and reinforce a model of science that is holistic, analytical and unrestricted by sub-disciplines (Solomon, 1993). The study upon which this thesis is based focused on providing ongoing and developmental laboratory experiences to students while allowing them an opportunity to examine more specifically how they learned by setting up their own assessment parameters. Students were encouraged to explore activities that brought forth and challenged common misconceptions in science and engaged them in collaborative problem solving which required multiple and creative solutions.

The research methodology that was thought to be the most appropriate for this particular study was action research. This type of research is, by its very nature, intended to be value-laden. According to McNiff (1998), action research is performed by researchers who explore and defend their educational values and aim to live their values in their work. The need for improvement in the current practices of science teachers, my own desire to initiate change, and my interest in examining student ownership of learning were the driving forces behind my research topic.

Collaboration can be viewed as a process which involves the coming together of ideas and opinions between people working towards a common goal. It should be noted that within the context of a classroom, the goal of a teacher is primarily to provide students with experiences that enable them to learn the prescribed curriculum. Realistically speaking, this overiding teacher goal is not necessarily congruent with goals that are set by students for themselves. It was my responsibility to ensure that science process skill development was a focus in the classroom. Students often concentrate on grades, pleasing the teacher and getting along with their peers, and these aims may not include incorporating a metacognitive long term learning approach in their laboratory experiences. Thus, true collaboration in the context of this study, whereby students inherently value the same goals as the teacher, could not always be met. The experiences in the classroom were intended to provide students with the opportunity to share in the development of the assessment parameters, and as such, to take on more responsibility for their learning. To obtain ownership of something involves gaining a sense of belonging and responsibility for it. If students are brought into and recognise the value and significance of developing their own personal understandings of scientific inquiry over the long term, then that sense of ownership can be more easily transfered from teacher to student. This research study describes a pedagogical approach that focuses on how student goals can be moved closer to the overiding teacher goal as set out by the curriculum for understanding scientific inquiry.

Research Questions

The main question being addressed in this study is:

What difficulties and benefits will grade 11 science students and their teacher experience when involved in collaborative and reflective assessment strategies that center around the development of science process skills?

Within the spirals of action research, a number of questions, many unanswered, evolved during the study:

- What will pedagogical strategies that support the development of scientific reasoning and process skills and include students in the generation of their own assessment parameters look like? What is the best way to implement these strategies? How can an assessment rubric be effectively modified over time in response to student feedback?

- Which classroom contexts are beneficial to the development of metacognition? Do student generated rubrics work in all science classrooms and at all grade levels? How much time is required before an appropriate classroom environment of trust and respect can be developed?

- What are the benefits and difficulties experienced by students as they work collaboratively through laboratories designed to confront possible misconceptions in science? What are the effects of student dialogue, group consensus and self-reflection on this process? How does student motivation effect the internalisation process?

- Do the perceptions of students concerning self and peer assessment agree with the perceptions of the teacher? Does increased metacognition and internalisation of the rubric standards have an effect on this agreement or disagreement?

Terminology

Many terms are used with specific intent and meaning throughout this study. The terms are described as follows:

Action Research: A form of collective self-inquiry specifically undertaken to improve the rationality and justice of the participants' own educational practices. As well, this type of inquiry attempts to provide deeper understandings of those practices (Kemmis & McTaggart, 1990). Action research requires collaboration with a group of individuals willing to critically examine the actions taken. By linking theory with practice and revising plan of actions as new ideas are brought forth, action research can be used to expand the sphere of the possible.

Authentic Assessment: Assessment which links the learning situation with the testing situation. Ryan (1994) describes this as the process of gathering and documenting student growth in a meaningful context.

Constructivism: A cognitive theory of learning which is based on the assumption that learners construct their own knowledge on the basis of interaction with their environment. As such, learning is a process in which students make meaning from concrete experiences, external information, and prior knowledge in a sociocultural context (Vygotsky, 1986). Learning and restructuring new concepts and theories can be difficult when they involve abandoning cherished knowledge, particularly if this prior knowledge includes misconceptions about the way the world operates (Cleminson, 1990). A constructivist approach to teaching involves engagement of the students' prior knowledge, exploration of problems, challenges and alternative ideas, and consolidation of new ideas into existing understanding by assimilation or accommodation.

Critical Thinking: A way of gaining knowledge which moves from the mere accumulation of facts towards knowledge as relative, contingent and contextual. This involves reasoning skills centred around the development of logical patterns and higher order understandings. Knowledge claims are evaluated using evidence, expertise and creditability of source (Harlen, 1999; and Westbrook, 1996).

Evaluativist Approach to Scientific Inquiry: A view of science which entails evaluation of the results of scientific investigations, alternative interpretations, and proposed explanations against evidence from nature. This evaluation involves reviewing experimental procedures, examining evidence, identifying faulty reasoning, pointing out statements that go beyond evidence and suggesting alternative explanations for the same observations (Hand, Lawrence, & Yore, 1999). Questioning, response to criticism and open communication are integral parts of the authentic science experience.

Formative Assessment: Assessment, gathered by teachers and by students examining their own work, used to adapt teaching and learning practices to meet identified needs. Assessment is formative when it is used to help learning (Wiggins & McTighe, 1998).

Metacognition: The process of thinking about and being aware of one's own thinking and learning processes (Thomas & McRobbie, 2001).

Rubric: A set of quality criteria and standards by which a significant outcome will be assessed (Popham, 1997). A student-generated rubric is developed with both the teacher and students working in conjunction to develop clear definitions of quality and the specific standards that must be met to achieve a particular level of ability (Andrade, 2000; and Skillings & Ferrell, 2000).

Scientific Literacy: To be scientifically literate allows one to be able to use scientific knowledge to understand and make decisions about the natural world. This involves an understanding of the nature of science and scientific inquiry, the role of reasoning, and the construction, dissemination, and application of scientific knowledge (Hand, Lawrence & Lore, 1999). Scientifically literate students that are writing in science should be able to demonstrate evidence of their learning, knowledge, and engagement with scientific inquiry. The writing process itself can be the means through which students communicate their understanding of and commitment to this form of inquiry (Holliday, Yore & Alvermann, 1994).

Science Process Skills: Abilities relating to identifying investigative questions, designing experiments, obtaining evidence, interpreting evidence in terms of the questions addressed and communicating the investigation process (Harlen, 1999).

Hypothetico-deductive Reasoning: A hypothesis, in the context of this study, is the necessary background theory required for understanding the nature of the science experiment being performed. Based on the evidence obtained through the investigation, students are then required to establish whether or not the hypothesis and its theoretical basis have been upheld, or if they need to be rejected or modified in light of the findings (Kwon & Lawson, 2000). Alternative explanations for the results which can be further tested are an integral component of this type of scientific reasoning. In order to use this form of scientific reasoning, students have to be willing to suspend their initial beliefs and be willing to test these beliefs through experimentation. It involves beginning from a broadly-based theoretical perspective and working down to a specific application. It is thus primarily a deductive rather than an inductive approach to science.

Chapter 2: Literature Review

Overview

In order to be able to fully understand the nature of this study, more than one area must be acknowledged in my literature review. An examination of the broader topics of critical thinking, constructivism, and current brain research will allow for the development of a working philosophical framework within my research. Because this study centers around laboratory work, a review of educational research on the nature of science, scientific literacy, scientific inquiry and process skill development is important. Finally, an understanding of formative assessment, rubric formation and student metacognition is fundamental. As I defined my search to narrower parameters, I was less able to find specifically relevant studies. Formative assessment which combines self-reflection, student-generated rubrics and science process skills appears to be a little used pedagogical approach in science education literature.

Critical Thinking and Constructivism in Science Education

Critical thinking and the ability to predict events is crucial to scientific thought. Critical thinking allows us to move from the mere accumulation of facts towards gaining an understanding of knowledge as relative, contingent and contextual. This type of reasoning involves skills centered around the development of logical patterns and higher order understandings. Knowledge claims can be evaluated using evidence, expertise, experience, and creditability of source. We can classify objects into general categories, estimate general solutions, and adapt preliminary decisions to new information and further applications (Hand, 1999).

Developing critical thinking skills in science classrooms can be approached using a constructivist learning design. Constructivism is a cognitive theory of learning based on the assumption that learners construct their own knowledge on the basis of interaction with their environment. This can lead to mistakes, over generalizations and misconceptions. Children come into our classroom with an established world view, formed by prior experiences. They are emotionally attached to them and will not give them up easily. Challenging, revising and restructuring one's world view requires much effort. Learning and restructuring new concepts and theories can be difficult when they involve abandoning cherished knowledge, particularly if this prior knowledge includes misconceptions about the way the world operates (Brooks & Brooks, 1993; Cleminson, 1990). The ability to perform higher level thinking and reasoning within a scientific context may be imperative to the learning of counter-intuitive concepts.

Vygotsky (1986) suggested that students' constructions (spontaneous concepts) and experts' constructions (scientific concepts) develop in reverse directions. A spontaneous concept works its way up until it reaches a level that permits a person to absorb a scientific concept, and scientific concepts work their way down, supplying logic and structure to spontaneous structures. Vygotsky explains:

> The child becomes conscious of his spontaneous concepts relatively late; the ability to define them in words, to operate with them at will, appears long after he has acquired the concepts. He has the concept (i.e., knows the object to which the concept refers), but is not conscious of his own act of thought. The development of a scientific concept, on the other hand, usually *begins* with its verbal definition and its use in nonspontaneous operations - with working on the concept itself. It starts its life in the child's mind at the level that his spontaneous concepts reach only later. (1986, p.192)

Problem solving tasks are critical to the growth of student constructions but the two types of constructions must be brought together in teacher-student dialogue. When students are involved in group activities requiring problem solving, decision making, and invention, they develop their own personal understandings. When left on their own, these personal understandings may not be congruent with current scientific understandings. Ideas which are constructed at a particular time and at a particular place may in fact clash with experts' constructions and should not be permitted to stand.

Conversely, teachers who present information as a discovered stable reality that must be accepted send a clear message to students that their own constructions are trivial and often incorrect. It is through an integration of the two approaches that meaningful conceptual understanding can occur. Vygotsky states:

> The development of a spontaneous concept must have reached a certain level for the child to be able to absorb a related scientific concept...In working its slow way upward, an everyday concept clears a path for the scientific concept and its downward development. It creates a series of structures necessary for the evolution of a concept's more primitive, elementary aspects, which give it body and vitality. Scientific concepts, in turn, supply structures for the upwards development of the child's spontaneous concepts towards consciousness and deliberate use. (1986, p.194)

Students must be able to negotiate differences of opinion, seek consensus, and challenge their constructions in light of the experts, and the teacher needs to discuss experts' constructions in relation to emerging student constructions. Zahorik (1997) describes this idea of constructivism as critical teaching, whereby constructions of both types are examined for inadequacies and errors. The object of a lesson is not to conclude with a correct answer, but rather to extend the discussion. When students can compare and contrast their constructions with those of the experts they gain insights into both and can begin to reconceptualise their constructions in the direction of the experts, or come to an increased awareness of the viability of their own conceptions. For example, when teaching evolutionary theories in biology, teachers need to stress that existing theories such as Darwin's are not absolute statements of fact, and that there are many other student-derived ideas that might be plausible, within the framework of logical scientific reasoning. Allowing students to use a Lamarckian evolutionary argument of use and disuse for the formation of adaptations in animals as a legitimate theory promotes a common and logically faulty misconception. Through an examination of the history of the development of evolutionary theories students can come to a greater understanding of why certain theories have been discarded in favour of others. Any new ideas constructed through discussion concerning evolutionary theories by students can then be evaluated along a common framework. Learning through constructivism is therefore a process in which students make meaning from concrete experiences, external information, and prior knowledge in a sociocultural context.

The learning process described in this study is not about showing students how to become experts in scientific inquiry. The action research spirals describe an ongoing developmental process whereby students examine and begin to recognise the levels at which they are currently operating, and to establish specific ways in which they can demonstrate improvement over time. Expertise is not something that is eventually gained, but rather it is something which is developed over the long term.

Brain Research and Learning

Many of the neuronal connections that process cognition develop after birth as our brain gradually adapts to its environment (Sylwester, 1995). Innate abilities such as language are formed during fetal development, and networks dedicated to these areas are either strengthened from experience or weakened from disuse over time. Current research on the maturation of the brain appears to agree somewhat with Piaget and his stages of development. A back to front brain maturation occurs in the cortex with the sensorimotor and concrete abilities developing first at the back of the brain, followed by formal operations concentrated in the front half. Objects and events in time are also processed along this back to front axis, with memory (past) at the back of the brain, critical thinking and problem solving (present) at the middle of the brain, and planning and rehearsal (future) at the front of the brain that matures during late adolescence (Sylwester, 1995). There is also a developmental release of myelin, which surrounds neurons and aids in the efficiency of electrochemical message transference. This growth appears to occur in spurts, however, and varies in terms of years depending on the individual until about 30 years of age (Sprenger, 1999).

Kwon and Lawson (2000) recently conducted an experiment studying the possible relationship between growth spurts, critical thinking, and conceptual change with 210 students ages 13 to 16 in Korean secondary schools. Specifically, they studied the maturation of the prefrontal lobe and its correlation with scientific reasoning ability, the rejection of previously held misconceptions and conceptual changes in thought relating to the study of air pressure. The 13-14 year olds, presumed to be within a plateau period of prefrontal growth, did not show any improvement in their abilities to reject intuitively-derived misconceptions. The 15-16 year olds, presumed to be in a developmental growth spurt, demonstrated marked improvements in hypothetico-deductive reasoning. Studies such as this have an important role to play in the incorporation of effective constructivist teaching strategies within a science classroom. If students are unable to suspend their initial beliefs or construct arguments on their own, conceptual change cannot occur. This may have consequences not only on how we teach these counter-intuitive concepts, but when we teach them.

When neural cells connect with dendritic branches, they are in closer proximity and can be used over and over again effortlessly. These new synapses occur after learning. When we take in new information, our sensory system activates a variety of different yet related brain networks that are arranged in columns within the cerebral cortex. Simultaneous activation of these networks can affect the firing rates of neurons and the amounts of neurotransmitters that are released (Jenson, 1998). The brain itself constantly seeks connections between what is new and what is already known. Our long term memory is thought to be stored in at least five different pathways (Pinker, 1997). The way we prefer to receive information will affect the amount of neural networks in a given area.

Cardellichio and Field (1997) suggest that when students have the opportunity to select and assimilate enough data to force them to challenge misconceptions and to create strong accurate conceptions, neural branching in the brain will be accelerated, while rigid presentation of data without the opportunity to make any sense of it accelerates neural pruning. Lowery (1998) argues that rehearsal, rather than repetition, allows the student to transfer what they have initially learned to increasingly complex novel situations. Repetition takes place when the same idea is presented over and over again. This approach allows for accuracy and efficiency when learning such things as multiplication tables, but has limited transferability. Rehearsals reinforce what has been learned previously by examining a similar but not identical idea. In this way, prior knowledge is reinforced, while at the same time something new is being added to increase the likelihood that the knowledge gained is not task-specific and thus more easily transferable to different contexts. When the connections between storage areas within the brain are strengthened through rehearsal, they have a lesser tendency to disengage or fade away (Diamond & Hopson, 1998). Sequentially developed concepts that are progressively built through increasing grade levels can help students to relate new knowledge to prior knowledge (Lowery, 1998). When students are able to confront and disprove their misconceptions by actively testing them out, they can promote long term depression of the synapses responsible for the initial misplaced learning. Facilitating trial and error experimental projects, and allowing students both to make mistakes and to reflect upon them, appear to be brain-compatible learning strategies. Students themselves make the wrong connections less likely, change their receptivity to previously misleading stimulations and alter their synaptic connections.

Enrichment brain research suggests that the brain will vary the way it develops depending upon the way the environment is changed. The effects of environmental stimulation and deprivation on the cerebral cortex have been extensively studied in rats for the past 30 years. The brains of young rats exposed to enriched or impoverished environments have been shown by researchers to have marked differences in the thickness of their cortexes, the size of their neurons, the number of interneural connections made, and the overall supply of glial cells (Diamond and Hopson, 1998).

Brain development showed the most positive growth when rats were given challenging environments combined with social interaction (Jenson, 1998). It is important to note, however, that an enriched laboratory built specifically to mimic the natural habitat of rats is a far cry from what may constitute an enriched environment for learning in the classroom. Much more research has to be done specifically in educational contexts to determine which experiences might provide the best potential for developing the brains of children and adolescents. Greenough and his colleague interpret an enriched environment for learning as one that offers changing instructional strategies, challenging experiences, and social feedback (Greenough & Anderson, 1991).

Challenging counter-intuitive concepts and misconceptions in science can create feelings of tension and stress in students. Emotion has a powerful influence on what and how we learn. Information that is gained through our five senses is filtered through our reticular activating system (RAS), and then goes to the thalamus for sorting. The cortex then decides whether to act upon this information or to store it in long term memory. If this information is stored, it is then relayed to the hippocampus where it is catalogued and filed. If the information has emotional context, it is also sent to the amygdala. But if the situation is highly emotional, the information will be sent directly to the amygdala before the cortex has a chance to process it. This will then initiate the fight or flight stress response and the release of chemicals by the pituitary gland that block higher reasoning and planning skills (Sylwester, 1995). Our stress mechanisms will not differentiate between emotional and physical danger and thus can often be maladaptive. Fear sets up a tug of war between the quick emotional response and the more analytical mechanisms in the brain. Chronic high cortisol levels due to excessive stress can lead to the destruction of neurons in the hippocampus associated with learning and memory. As well, short term stress-related cortisol levels in the hippocampus can lead to an inability to distinguish between the important and unimportant elements of a memorable event (Sprenger, 1999).

When the body's stress chemicals block the neurotransmitters that help you to make logical connections, this can cause the brain to shift from higher to lower levels of thought. This is known as "downshifting". In these cases, it may be impossible to foster higher order thinking and creativity. It has been suggested that downshifted students may be able to memorize well because the repetition provides a sense of safety when feeling helpless (Pool, 1997). Emotion can also be a positive motivator in the classroom as it can drive attention, which in turn drives learning and memory. Addressing the emotional side of learning by offering challenging yet safe experiences and avoiding threats may improve student success in school. It is important to ensure that progressively abstract science concepts that are linked with common misconceptions are presented in such a way that students encounter challenges for which they are adequately equipped. Students working in heterogeneous groups with teacher facilitation are given both social and academic feedback on ideas and behaviours. Feedback given in this way can help reduce uncertainty, increase one's coping abilities, and can lower the pituitary-adrenal stress response (Sprenger, 1999).

Newer science philosophies now examine science as an ever-changing body of knowledge. As such, educators need to look for alternative approaches to solving problems within a scientific context, and avoid promoting the idea of having only one correct answer. If educators continue to dominate the instructional and evaluative decisions and activities, an enriched educational environment may not be having the intended effect. The enrichment studies imply that it is not enough to just be presented with a stimulating experience. In order for changes to be seen in the brain, students need to create and directly interact with their environment. They need to have the opportunity to do more than just listen to the experienced teacher's constructions. If our brains develop individually through growth spurts that are distributed across specific age periods (Sprenger, 1999), then we need a more dynamic and flexible skills framework more appropriate to how our brain actually grows. This view works well with the model of the brain as a developmental web, with parallel thinking strands occurring through Gardner's multiple intelligences (Armstrong, 1994). Fischer and Rose (1998) suggest that rather than progress through stages, at each level, a child can build a new, more complex kind of skill or understanding in diverse domains. There are no instant changes in understanding abstract concepts, but rather children show a cluster of changes over several years. As well, people vary enormously in the skill levels they use every day, only occasionally functioning at their optimal level (Fischer & Rose, 1998). If the brain is constructed based on our individual experiences and innate abilities in certain domains of the brain, then differentiated classrooms that attempt to address many ways of learning may be the most brain-compatible.

The Nature of Science

How we view science affects how it is taught. The nature of science has been re-evaluated over the last forty years, and yet this has not been reflected in contemporary science curricula (Cleminson, 1990). Science educators need to have both an historical perspective and an understanding of the current philosophies of science in order to present a balanced and authentic view of this subject. Apple (1976) suggests that if the scientific community works by way of collective skepticism and conceptual revolutions, then science in schools should reflect this inherent conflict. Science education too often denies students the opportunity to criticise or question the legitimacy of scientific assumptions. Contemporary science philosophies suggest that scientific observations are not neutral events, but are shaped by our beliefs, previous knowledge, and social interactions. Thomas Kuhn (1962) suggests that a closed scientific community exists which operates within a dominant paradigm composed of shared beliefs, values, techniques, and theories. Periods of revolutionary science, such as the emergence of the theory of quantum mechanics in physics, are required to bring about changes to the dominant paradigm. In Kuhn's view, the activities of scientists are influenced by both social and personal interactions. Karl Popper's progressive view examines the testing of theories through techniques that involve falsification rather than verification (Popper, 1959). Scientific theories, are thus regarded as fallible and ever-changing. Other philosophers, such as Lakatos (1970) and Bronowski (1978), include a further humanistic component to scientific discovery, with the notion that scientific direction requires creative imagination. In order to make the study of science meaningful and relevant to students, we must involve them in a creative process of self-constructed learning. Along with appropriate teacher-facilitation, theories need to be presented as scientific ideas rather than facts. Students should be encouraged to challenge knowledge rather than regurgitate it. Open-ended laboratory experiences can provide students with the opportunity to look for creative solutions and to critique common counter-intuitive misconceptions.

Laboratory work in the physical sciences is typically presented to students as a set of instructions to be carried out and performed, with the result being a set of observable and predictable outcomes that mirror a particular theoretical concept being studied in the classroom. For example, in chemistry, students are commonly asked to test out the properties of various elements and then come up with a set of standard characteristics for metals, non-metals, and metalloids. Recipe book labs performed in this manner deny students the opportunity to question the design of the experiment, examine further ways to test out ideas, or make deeper connections with the concepts being studied. Incorporating student participation in the design and procedure of an experiment would allow for a more constructivist approach which takes into account students' prior knowledge. As well, possible misconceptions regarding the concept itself would be more likely to arise and could therefore be acknowledged and discussed through teacher facilitation and further experimentation.

In science classrooms, the focus is often on objectivity and reproducible results. Many theories are taught as immutable facts. This presents students with a particular way of looking at science and technology which is problematic. When using an STS approach in the science classroom, it is important that educators develop an awareness of the current underlying world view that permeates the way modern science is conducted. According to Jardine (2000), our science curriculum in Canada embodies images which are particularly eurocentric. He further suggests that if our truths about nature are based on the dissection, separation, and isolation of what is being studied, then discourse on science and technology inevitably lacks contradiction, ambiguity, and a sense of the inter-dependencies that exist within natural phenomena (Jardine, 2000). Thus, inherent epistemological assumptions exist throughout our teaching which promote the use of reason and rationality to dominate, subjugate, and use the earth as we please. If we work towards a purely objective way of understanding our dependency on our planet, we ignore understandings of how to live within it. A focus on reductionism, aggression, and the organization of parts to the whole forms a world view that promotes a technocratic industrial society where the scientific method reigns unchallenged (Selby, 2000). When science education focuses on facts rather than essences and contexts, it mirrors this particular world view. The aim of science education should not be to perpetuate a world of unquestioning consumers within a technocratic society. Brouwer (1992) suggests that citizens encouraged to be passive consumers can be vulnerable to exploitation by the producers of technology when that technology is presented from a materialistic standpoint. It is the responsibility of educators to incorporate a broadly based examination of science which includes integrated multiple epistemological approaches and acknowledges the interconnectedness of complex systems within our world. In his book examining the culture surrounding agricultural practices in the United States, Berry (1986) suggests that new breakthroughs in science and technology appear to be so lucrative that they diminish the possibility of any interest in prevention. If we as educators discuss technology in bits and pieces over isolated science units across the secondary science curriculum, then we reinforce the prevalent view that examining individual parts can give us an adequate representation of the whole.

Scientific Literacy

To be scientifically literate allows one to use scientific knowledge to understand and make decisions about the natural world. This implies that students should have a multidimensional perspective about science and its relationship to other fields of study, and not just familiarity with procedural and conceptual knowledge (Hand et al., 1999). An overarching vision for effective science teaching and learning needs to incorporate understandings of the nature of science and the roles of reasoning. Language is ambiguous; by its very nature it can create discourse and prevent a single pathway to knowledge. Gadamer (1993) suggests that language is an important vehicle in opening up questions rather than drawing single conclusions. He writes; "the essence of the question is to open up possibilities and keep them open" (Gadamer, 1993, p.299).

The social context of learning may be a vital part of this process. Sutton (1994) explains that because language is interpretive, discourse can be used to produce a community of thought when ideas are shared. Vygotsky (1986) suggests that words play an important part in the development of thought, in that when a learner attempts to impart knowledge to another, the level of linguistic competence is heightened, which in turn impacts the nature of the learner's understanding. Small and large group discussions regarding observations made in the natural world are a vital component in the perception of scientific concepts. As well, writing about those discussions has great potential to enhance learning.

Writing and responding to the writing of others can develop reasoning and promote personal meaning making by providing interactive and constructive opportunities to clarify knowledge (Hand et al., 1999). Writing laboratory reports can allow students to broaden their understanding of scientific methods and how data is both represented and analysed. A transformational approach to writing should be recursive in nature, including the elements of reflection, revision and reorganization. Classroom writing in science often falls short of this, as it often emphasizes knowledge telling, recording observations and information and transmission of recalled information (Holliday, Yore, & Alvermann, 1994). These types of writing tasks lack a degree of mental engagement and as such, do not promote meaningful learning. Classroom science, as experienced through laboratory work, can be associated with authentic learning if it is accompanied by active discussion and transformational writing tasks that engage students in critical thinking and an evaluative form of scientific inquiry.

Scientific Inquiry and the Development of Science Process Skills

Scientific inquiry should involve evaluation of results, alternative interpretations, theoretical models, and proposed explanations. Students should be encouraged to review procedures, examine evidence, identify faulty reasoning, and suggest alternative explanations using a combination of logic and imagination. It is essential that students begin to develop and question their own epistemological beliefs about knowing, scientific proof, justification and logic. The epistemological beliefs of students should be examined in terms of a continuum of knowing which moves from knowledge obtained from outside the self to self as knower, through interactions with others, prior knowledge, and concurrent experiences with nature (Hand et al, 1999). How one reasons and uses critical thinking can then influence conceptual understanding and science literacy. There is also a need for framing writing tasks in such a way that students are encouraged to develop multiple causal hypotheses about issues and this approach may help to develop higher order thinking and reasoning skills.

When students are asked questions about their laboratory work, they often respond with generalised answers which lack understanding, or further entrench their previous misconceptions (Westbrook, 1996). Students are rarely involved in any kind of mental engagement or reflection on the value of their experimental observations, and most students tend to focus on completing the task rather than learning from it (Zohar, 1998). Factors which may improve student learning during classroom experiments may include adequate background knowledge, the extent of student ownership, giving the students sufficient time to plan, implement and conclude their work, and student awareness of the purpose and aim of laboratory work (Berry, Mulhall, Gunstone, & Loughran, 1999). Learning with understanding in science involves testing possible explanatory ideas and using them to make predictions, pose questions, design investigations, collect evidence and interpret results. Science educators can promote meaningful learning if they include more opportunities for using process skills, encourage critical review by students of the science process, give students examples of work which meet criteria of quality and engage in metacognitive discussion about procedures so that students can see the relevance to other investigations and the way they were performed (Harlen, 1999). An authentic science experience, in the context of this study, is one which requires students to engage in activities where they must construct, discuss, evaluate and then communicate their knowledge of scientific concepts on the basis of evidence gained through scientific inquiry.

Formative Assessment

Assessment is authentic when the testing situation parallels the learning situation (Ryan, 1994). Evaluation should not be a one-way power relationship whereby teachers impose their values on students. Instead, it should be a process of gathering and documenting student growth in a meaningful context for students, teachers and parents. Wiggens (1989) suggests that for assessment practices to be authentic, they should be structured to provide the needed information to direct learners to a mastery level, and to further inform learners about the manner in which they learn. Formative assessment is focused on using work gathered by teachers and by students examining their own work to adapt teaching and learning practices to meet identified needs. The goal of this type of assessment is to help with learning. There is no one right answer or immutable truth to objectively tally student grades. Students also have an important role to play in selecting evaluated material and employing their own judgments on their work. They are invited to become active participants in their own assessment. The goal is to examine the entire context of learning and what the student can accomplish. Wiggens writes:

> Rather than rely on right/wrong answers, unfair 'distractors'
> and other statistical artifices to widen the spread of scores,
> authentic tests ferret out and identify (perhaps hidden) strengths.
> The aim is to show students what they can do. (1989, p.711)

Rubric Formation

In this study, rubrics are examined as a means through which an authentic formative assessment strategy is employed in eleventh grade science classrooms. A rubric is the set of quality criteria and standards by which a significant outcome will be assessed. Rubrics are typically developed with the teacher and students working in conjunction, or are given to the students in advance of their beginning a unit of study, to assist them in understanding the curriculum expectations. Either way, students have the rubrics in their hands over an extended period of time, with the intent that they will come to internalise the expectations. Rubrics therefore serve a pedagogical as well as a purely evaluative function, and are created in a very particular way.

When the rubric development process is opened up to include students, they are required to analyse quality work and its critical components, they begin to internalise the expectations inherent in their assignments and they often become better performers themselves (Skillings & Ferrell, 2000). For any given unit, educators should clearly be able to state what overarching understandings are desired, which essential questions will be addressed, what evidence will be used to demonstrate this understanding and which planned learning experiences and instruction will equip students to demonstrate the specified understandings (Wiggins & McTighe, 1998). An effective rubric should be able to reveal problems that students actually experience. Vague definitions of quality do not allow students to spot their own weaknesses or give them concrete ways to improve their writing. Rubrics are a good instructional tool because the are easy to use, they make teachers' expectations clear, they provide informative feedback about areas of strength and in need of improvement and they support learning and the development of specific skills and higher level understanding. Andrade (2000), suggests that there are effective strategies to use when designing a rubric which include looking at models, listing criteria, combining the criteria, articulating levels of quality, creating a draft rubric and revising the draft. She also suggests that students be involved in the rubric-generating process and that a careful, specific student self-assessment technique should be used with any ongoing assessment strategy. The criteria involved in the construction of a rubric include addressing important learning outcomes, reflecting outcomes that are teachable and limited to a feasible number of dimensions, recognizing conceptions of 'excellence' and utilizing clear language that is understandable to students, parents and educators. In order for students to be aware of their own strengths and weaknesses, it is imperative that they be involved in the evaluation process. By actively participating in the rubric formation they should gain a better understanding of the required learning outcomes, and this in turn should enable them to better reflect on their own progress. If students are not included in their own assessment, they often feel themselves put into a reactive rather than proactive frame of mind upon receiving their grades. If we want to focus on enduring understandings, then the students themselves must be invited to take on a more active role in their own education.

Although many science educators are using rubrics, the assessment focus is still on the teacher, rather than on the students. Almost all of the research related to the development of classroom rubrics found during my literature searches focused on learning to write in elementary classrooms (Skillings & Ferrell, 2000; Wiggins &

McTighe, 1998) or examining essay writing in secondary humanities classrooms (Andrade, 2000; Popham, 1997) , rather than science. The vast majority of the research on rubrics do not identify student involvement as a key component in their classroom use.

Metacognition

For the purpose of this research, metacognition is defined as the students' knowledge, awareness and control of their learning processes (Baird, 1990; Gunstone & Mitchell, 1998). Teaching pedagogies that incorporate student metacognition may lead to improvements in learning outcomes because learners are most successful when they understand and have access to their learning strategies and insights into their own capabilities (Brown, 1994; White, 1998). Educational contexts such as student perception of their classroom environments, assessment demands and the broader school culture can all influence students' abilities to enact their metacognitive knowledge (Thomas & McRobbie, 2001). If overcoming misconceptions in science is often a difficult task for students, a self-reflective approach could offer opportunities to decrease levels of student frustration. True science, by its very nature, can be frustrating when there are no apparent reasons for experimental outcomes. Metacognitive activities can allow students to discuss their emotions through personal reflections. A journal for writing about the process itself can be used as an emotional outlet when uncertainty levels are high. Emotion, however, should be incorporated in safe measures to provide motivation and promote active student engagement. Motivational aspects have been demonstrated to be a crucial element in the development of metacognition and conceptual change in students (Anderson, 1997; Dweck, 1986; Garner, 1990). Experiments that are student-derived can provide a framework for social interaction and metacognition. When students are involved in rubric formation, and peer and self assessment, they are able to examine their strengths and weaknesses according to specifically-derived criteria. Metacognitive activities which allow students to reflect on their awareness of their knowledge of science process skills and evaluate their progress over time should gradually deepen their conceptual understanding of scientific inquiry.

Conclusion

From my brief review of the literature it appears that, although on a general basis much research has been done on how students learn science, how science process skills are developed, and how specific science concepts are best addressed in the classroom, little research has yet been done to incorporate either across discipline strategies in science laboratory work or student-collaboration in science assessment practices. Since laboratories are common to all science classrooms, it would be helpful for students to not only be given a rubric to follow, but to help in its development. Although many science educators are using rubrics, the assessment focus is still on the teacher, rather than on the students. The philosophy behind authentic assessment and learning needs to be promoted between the different science disciplines as well as other subject areas and across grade levels.

Chapter III: Research Methodology

Choosing Qualitative Inquiry

My own underlying epistemological framework regarding pedagogy and assessment determined the kind of research methodology chosen for this study. According to Creswell, a quantitative study is an inquiry which is based on "testing a theory composed of variables, measured with numbers, and analyzed with statistical procedures, in order to determine whether the predictive generalizations of the theory hold true" (Creswell, 1994, p.2). Quantitative methodologies rely on static designs which test theories and hypotheses in a cause-and-effect order. If I were posing a directional hypothesis stating that there will be a significant difference in achievement in my students when they begin to examine how they learn while they develop scientific process skills, I would then have to use a quantitative methodology that would attempt to test for either a change in metacognition, hypothetico-deductive reasoning skills, or achievement on standardized science examinations. This would require an experimental and control group, both taught by me, with one using a traditional approach to experimentation (control group) and the other employing the student-generated rubric pedagogy (experimental group). These two groups would initially be given a pretest for comparison purposes, followed by experiences of the different pedagogical approaches, and then a post test to see if the pedagogy made any difference to the experimental group's understandings. The data would then be statistically analyzed for correlation and probabilities to see if the changes were significant or due to chance.

The difficulty with this approach is that it cannot adequately get at the essence of what I am questioning. Quantitative methodologies are collected and interpreted in terms of their reliability. According to Elliot (1991), this ends-means technical research orientation defines outcomes or products without fully examining the processes of change. When process is subordinated to product, knowledge of that process is largely derived from inference. An ends-means orientation that seeks to eliminate variables in order to identify cause-and-effect relationships can be severely limiting when studying human interaction. According to Elliot (1991), educational research of this nature has led to the prevalent view of evaluation as an objective entity. In this study, I am examining less normative approaches to assessment which cannot readily be classified in a standardized way. The use of a survey as a quantitative technique may provide many different opinions, but fails to answer many of the deeper questions about what is valued and whether teachers and students share common meanings of scientific inquiry. Surveys can show trends, but they do not question the tenets of cause-and-effect assumptions. Although my study centers around change, I am not trying to compare one pedagogical practice with another, or to examine its effect on traditional assessment outcomes and standardized achievement scores.

Qualitative research attempts to better understand human experience and is "based on building a complex, holistic picture, formed with words, reporting detailed views of informants, and conducted in a natural setting" (Creswell, 1994, p.2). This research orientation assumes the existence of multiple realities and allows for the interaction of the researcher with those they study. According to Berg:

> qualitative procedures provide a means of accessing unquantifiable facts about the actual people researchers talk to...qualitative techniques allow the researchers to share in the understandings and perceptions of others and to explore how people structure and give meaning to their daily lives. Researchers using qualitative techniques examine how people learn about and make sense of themselves and others. (Berg, 1989, p.6)

In this form of inquiry, problems are explored for which the variables may be largely unknown and often emerge as the study unfolds. Data gathered in this manner is context bound, and the focus on context can then shape the understanding of what is being studied (Creswell, 1994). This research study sought to explore the experiences of students as they learned and reflected upon science concepts constructed through scientific inquiry, and to further examine the effects of including those students in the generation and use of an assessment tool for developing science process skills and critical thinking. Exploration such as this does not have a quantifiable measurement, such as the degree of change in science reasoning abilities within the students, as its end goal. Instead, documented descriptions of the changing perceptions of the students and myself as teacher in the context of this particular learning environment became important tools for reaching greater understanding. Qualitative inquiry was the means through which I could reflect upon and transform my own educational practice.

Selecting an Action Research Orientation

Action research involves applying collective self-inquiry to improve the rationality and justice of the participants' own educational practices, and also attempts to provide deeper understandings of those practices (Kemmis & McTaggart, 1990). According to Emily Calhoun, action research specifically "asks educators to study their practice and its context, explore the research base for ideas, compare what they find to their current practice, participate in training to support needed changes, and study the effects on themselves and their students and colleagues" (Calhoun, 2002, p.18). As such, this research methodology was well-suited for my study. My research was based on the belief that student assessment in science can be improved by employing strategies that enable students to become more actively involved in their own assessment. Improvement links the manner in which students learn and the manner in which they are assessed, and its meaning in this context connects with the notion that assessment strategies should be meaningful for both teacher and student (Aoki, 1984). According to McNiff, action research should be concerned with praxis, rather than practice, where praxis is "informed, committed action that gives rise to knowledge rather than just successful action" (McNiff, 1998, p.8). Informed action stems from incorporating and taking into account the views of others, and committed action implies that the values taken are examined and argued. In my view, rather than following a linear path to improvement, the action research process instead opens the door to greater possibilities.

Structural and procedural reliability for this study was obtained through a definable methodology typical to action research involving a cyclical process with spiral steps (Elliot, 1991; Feldman, 1996; McNiff, 1998; Sagor, 1992). I have identified two concurrent research spirals (metacognitive and science process skill development) occurring throughout this study. Each spiral incorporates four different stages of the typical action research cycle: planning/revision, acting/observing and reflection (Elliot, 1991). Each plan of action within the study was designed to be forward looking, constructive and flexible enough to respond to modification.

Role of the Researcher

The study included myself, the teacher, as reflective practitioner involved in working together with students in determining assessment practice. As a teacher, I cannot completely step out of my pedagogic role to become the researcher. Practitioner reflection and action are two aspects of the same process. In this form of action research, participants affected by the planned changes have the primary responsibility for deciding on the course of critically informed action which seems likely to lead to improvement, and for evaluating the results of the strategies attempted (Kemmis & McTaggart, 1990). The study focused on critically examining the actions taken using student feedback, teacher field notes and ongoing reflection to find themes and create a platform for new questions and subsequent research spirals. An autobiographical narrative formed a small part of my research methodology, as I kept a journal of my feelings and reflections as the study unfolded. Through writing about the experience I tried to bring out more meaningful insights and to question whether or not, as teacher, I was manipulating or guiding the process. The research represented a personalized journey for me, because it informed my own teaching practice, changed my own perspective about students and encouraged me to give up control in my classroom. Critical reflection was a difficult emotional process because it involved reexamining my perceptions of myself as a science teacher. Thus phenomenological and narrative elements formed part of the research approach. However, my aim was not so much to get at a story of myself in the research, or to understand the essence of metacognition and scientific inquiry. It was about changing the reality of my classroom. The knowledge gained from the process is intended to inform my own educational practice in the future. I hope to further incorporate change across different science classrooms and age levels. My roles throughout this process, therefore, moved between teacher, initiator, facilitator, collaborator, motivator, reflective researcher and hopefully, disseminator of possible change in the future.

Gaining Entry

An important part of action research includes gaining entry. This involves establishing a group of people with whom the researcher can gain trust and commitment. I initially began the research cycle with two semestered eleventh grade chemistry classes of 35 students each (approximately 15-16 years of age), where the students were motivated to do well academically. Documentation of this portion of the research study occurred over a period of five months. Subsequently, I moved to a different school within the same district. I interrupted the beginning of the next research cycle by six months because I felt that I needed to gain the appropriate degree of entry in this new school. The administration, students and fellow staff members were not familiar to me, and the courses I was selected to teach were not as appropriate to the research I had in mind. By waiting six months, I felt I had better access to the particular grade level, the number of specified students and the appropriate academic science course required for my action research study. A semesterised eleventh grade biology class of 24 students was chosen for the second cycle of the research study over the next five months. The move to a different school environment allowed me a greater opportunity to examine the effects of classroom context, abilities of students and the transferability of the pedagogical approach to a different science course. My current administrator, professors and colleagues were aware of the study, and were encouraged to offer their comments and reflections as well. Before gathering any data from the students, I concentrated on establishing classroom atmospheres that encouraged mutual trust, respect and familiarity.

Participants Involved

I felt it was important to include a collegial component to this project for the purpose of gaining a deeper understanding of the function of rubrics and to generate an initial framework for planning. At the beginning of the study I chose a colleague working at a different high school who was familiar with developing student-generated rubrics in his English classes. A letter of introduction was provided explaining the nature of the study and the extent of the commitment required. Upon his consent, an interview was subsequently scheduled and the resulting dialogue was used to help formulate a working definition for the rubric, its criteria and standards, as well as the classroom plan of action.

When the researcher takes on the role of participant observer, a central issue to conducting the research is to ensure that the methodology and the aims of the research do not differ from the educational aims of the student participants (Altrichter, 1993). The research was designed to be compatible with the required Chemistry 20 and Biology 20 curricula, and thus I felt that the students were not being harmed by participating in this study. Specifically, the chemistry concepts examined included the Law of Conservation of Matter, the empirical classification of elements and compounds, and qualitative methods of identifying compounds. The biology concepts covered included the disproving of abiogenesis and the formulation of the Cell Theory, osmosis and qualitative methods of identifying food types. A summary of the specific plans of action occurring within the Chemistry 20 and Biology 20 classrooms can be found in Appendix D. All students in the classroom were required to take part in the investigations and write about their experiences as part of their regular course work. Although students could not decline from doing the work, as voluntary research participants they did have the right to decline from having their work used as data for the study at any time.

Permission for the laboratory work and student reflections gathered specifically from the Chemistry 20 student participants was obtained one year after the completion of the course, in the spring of 2002. I felt at this time that a useful comparison could be made between the chemistry and biology classrooms. Several students and their parents were asked, through a letter of introduction explaining the nature of the research study, if they would allow their previous year's school work to be used as data. The students were specifically chosen on the basis of the quality and variety of their written work, their effort in giving in-depth responses in their reflections, their analytical abilities in assessing other's work and their different opinions of the process. Both genders were represented, and all of the students and parents approached agreed to have the work used in the study.

All of the students in my Biology 20 classroom were invited to partake in the study. Student participants and their parents were given a letter of introduction describing the study at the beginning of the course. I made it clear at this time, both verbally and in writing, that participation was voluntary and that students wishing to have their work withheld from the study would be able to do so without fear of consequences on their Biology 20 grades. All students, with consent from both their parents and themselves, agreed to be involved in the study at this time. Students were given their own letter of consent to ensure that they felt included and valued in the study; this was thought to be especially important since the study itself was about empowerment and internalisation of learning. The written data gathered from the student participants included laboratory work, and peer and self assessment of their work using the class generated rubric. Students were also asked to write learning logs that were ongoing throughout the study. They were asked to comment about how they saw themselves as learners, whether they felt they were benefiting from the experience, what they disliked about it and how they would change it. During the small group consolidation of the rubric, recorded audio tapes of student dialogue were taken and transcripts were made.

After several laboratory investigations and their subsequent assessment, six students were invited to be involved in a 20 minute audio taped, semi-structured interview with myself to provide deeper feedback. These particular students were chosen for the interview process based on the variety of their written work, their expressed opinions in the reflective learning logs and their degree of motivation. I informed students that their contributions were strictly voluntary and they were under no obligation to participate in the interviews.

Research Instruments

The choice of a particular method of research imposes certain perspectives on reality. For example, making direct observations of events assumes that reality is deeply affected by the actions of all participants, including that of the researcher (Berg, 1989). If every method is a different line of sight directed towards some point, then a more substantive picture of reality should combine several lines of sight. The layering of data needs to be gathered using multiple rather than single perspectives. This requires triangulation and validation of data. According to McNiff, triangulation involves getting "data from more than one source to use as evidence to support a particular explanation" (McNiff, 1998, p.42), and valid explanations are based on whether or not your claims can be substantiated by your evidence. By using a combination of my own perceptions (observational field notes and a reflective log), those of my students (student work, audio taped interviews checked by students, and reflective learning logs) and of a colleague (audio taped conversation checked by colleague), I attempted to maintain an appropriate degree of data triangulation throughout the process. By sharing my work with my university supervisor and other professors, I received constructive feedback regarding the credibility of my claims.

Researcher Journal and Field Notes

A researcher journal outlining my impressions of the progress and difficulties experienced throughout the research process was written and periodically reflected upon. The journal served as a record of my impressions of the changes seen in my classroom and during interviews. According to Elliot, diaries should be kept on a continuous basis, and should "not merely report on the 'bold facts' of the situation, but convey a feeling of what it was like to be there participating in it" (Elliot, 1991, p.77). Reflections help to reconstruct the event, but should also include such things as anecdotes, descriptions of verbal exchanges and introspective accounts of feelings and motives. They help to bring context and understanding to situations experienced. The diary can also be used as a concise time line, to illustrate general points, create raw data and chart progress (McNiff, 1998). In particular, my reflective writings allowed me to examine my actions and interpret my results. Concise field notes were taken before, during and after important events, such as the rubric collaboration process and group discussions during investigations. These field notes included a description of the context and the students involved, as well as my initial thoughts and feelings concerning what was observed. These were compiled into a sequential chart, with comments and reflections added periodically as the study progressed. Reflecting upon the observed events after a few days allowed for a new perspective, and this in turn helped determine the direction for the next research spirals.

Student Work

Several different laboratory investigations were performed by students during the course of this study. Initially, students were asked to do an open-ended experiment in small groups, compose a group write-up of their work which followed the scientific method of inquiry and present their design to the class. After a large class discussion comparing different designs, students were required to determine, through peer assessment, which design was the most effective and to explain why. Students were then asked to individually modify their initial write-ups to include a discussion of possible improvements to their designs, to address misconceptions challenged through group discussion and experimentation and to provide further possibilities for investigation. The student work was evaluated with specific feedback by myself as teacher and was photocopied for documentation purposes, so that a comparison could be made with subsequent student work.

After a discussion of rubrics and their uses, students were asked to individually compose criteria for a rubric template concerning the evaluation of science process skills (see Appendix E). In groups of three and four, students were then asked to collaborate and consolidate their work into a revised rubric. Two of the small group discussions were audio taped during this collaboration process and a transcript was made for further analysis. The core information from the compiled rubrics were extracted and incorporated into the finished class-created rubric.

The same small groups of students were then asked to perform a second experiment and to submit an individual write-up using the class rubric as a guideline. Each student was given a completion grade for the work itself, and the write-up was then given anonymously to a different student for peer evaluation using the criteria specified in the rubric. The students were specifically told that they would not be graded on their own lab work, but rather on their critical assessment of the lab they were given to mark. This was done in the hope of getting honest dialogue from the students without fear of repercussions on their own grades. During the evaluation process, students were required to give specific feedback on the paper itself, as well as include a separate page examining each of the learning outcomes. Students were asked to comment on each of the categories they felt best represented the quality of work being assessed (see Appendix F). The evaluation was examined by me, the teacher, and additional feedback was given to both the student whose work was assessed, as well as the student that did the assessing. Students were then given a chance to voice their opinions, reflect on the assignment as a whole and to assess their own work. The reflections given by the students were used to provide me with honest feedback and to help gain a sense of the effectiveness of the pedagogical approach in developing meaningful learning experiences. Discrepancies and consistencies between my own and the students' perceptions of quality in others and themselves were documented and analysed. The ability of students to recognize and correct common misconceptions was checked for specifically in this work. As the course progressed, students were asked to collect their work in a duotang and to write about their critical analysis skills and comment on both areas that they had specifically improved upon and areas that they still found difficult. These metacognitive journals were photocopied and used for analysis in the study.

Interviewing

Interviewing is a conversation with the purpose of gathering information. According to McNiff, "interviews have distinct advantages over a questionnaire because you can get richer feedback as a result of being able to probe further" (McNiff, 1998, p.100). Action research, by its very nature, involves a degree of uncertainty and change. A semi-structured interview operates under the assumption that the researcher does not know in advance what all the necessary questions are, and that all students may not find equal meaning in like-worded questions. This type of interview involves a number of predetermined questions asked in a systematic and consistent order, while still allowing the interviewer sufficient freedom to probe farther (Berg, 1989). Guidelines for effective interviews include using body language that values what is being said, having appropriate listening skills, giving verbal ques to encourage free talk, using language that is appropriate to the vocabularies of the subjects and providing brief and concise questions (Berg, 1989; Mcniff, 1998).

The in-depth, open-ended interview was audio taped and conducted with my teacher colleague occurred in his classroom over a period of two hours. The questions chosen centred around assessment, rubric formation, student metacognition, student empowerment and the transferability of this pedagogical approach to different classroom contexts (see Appendix B). An exact transcript of the conversation was made, and subsequent validation of both the transcript and its interpretation was conducted with this teacher. The transcript was then specifically used to create, reflect, and remodel the research plan of action that was ongoing in the classroom.

The 20 minute audio taped semi-structured interviews with the six biology students took place in my classroom at a time selected by each student to be most convenient. It was made clear both verbally and in writing that this extra commitment and participation in the study was voluntary and would not affect their grades in any way. I explained carefully to each student that rejection or discomfort with any aspect of the pedagogical process did not indicate any disagreement with myself as their teacher. At this time I also stressed the fact that honest responses were important for the validity of the data produced and that a variety of different perspectives was the main purpose behind choosing them as interviewees. All students appeared to understand the nature of the interview and were at ease and relaxed throughout as they shared their ideas and experiences. A few were very talkative and enthusiastic about their opinions and gave rich descriptions. All suggested, in one way or another during the interview, that they appreciated the fact that their opinions were valued and were glad to have had the opportunity to discuss them with me. Questions presented in the conversations were intended to indicate the direction of the interview, rather than to be an inclusive list of sequenced questions. These questions focused on examining the weaknesses and strengths of the rubric, possible ways in which the rubric could be improved, how they felt about evaluating themselves and others and whether or not they felt they were benefiting from the process (see Appendix D). The student responses and discussion structured the interviews, and my perceptions of the students' needs were checked throughout. As I acted as both teacher and researcher, claims of objective-observer cannot be made. A strong framework of trust had to be established prior to the interviews being performed. Credibility of the interview data was established through validation of the transcripts by the students. Student responses are highly contextualized and affected by such factors as their relationship with the teacher, their perceived importance in the class, the cohesiveness of the class and expectations placed upon them and accepted by them (Berg & Brouwer, 1991). As such, these responses can only serve as an indicator of what might occur in a classroom, rather than being representative of all students.

Analysing and Interpreting the Data

According to McNiff, in order to evaluate the impact and significance of any evidence gathered, it is necessary to keep a record of relevant pieces as you work through the project and to "write out the significant features and critical incidents of your situation that would act as clear indicators" (McNiff, 1998, p.64). During the study, some of the data analysis occurred simultaneously as it was being collected. This was imperative to the action research process as each of the planning stages within the spirals could not occur until the observations from the previous spiral were reflected upon. The plans were revised and modified based on this initial analysis. For example, the transcript from the teacher participant interview had to be written and then internally validated by my colleague before initiating the plan of action in the classroom with the student participants. During the validation process, this teacher added information and made some relevant changes to the interview transcript, and a richer conversation emerged as a result. The summary and interpretation of these dialogues enabled me to form a working definition of the function of the rubric generation process and to plan for effective strategies for its implementation. The revised action was based on both the previous experiences of my colleague and my review of the related literature. Similarly, dialogue collected from the student group conversations and interviews were a vital source of data for ensuring that revisions of the rubric reflected the needs and opinions of the students involved. The student interview transcripts were also validated by the students, although no changes were made at this time. An ongoing teacher log and extensive field notes were kept throughout these stages in order to record the descriptive details being heard, observed and experienced. These were written immediately following the interviews and were not present in the typed transcripts. Further reflection on these descriptions helped to provide a richer context to the interviews. My recorded impressions and perceptions allowed for greater interpretation of the meanings behind the transcribed texts. To ensure dependability and confirmability during data collection, I maintained regular discussions with a university professor considered an expert in the area of action research methodology.

Some of the decisions made in the study occurred as a direct result of my experiences with the students in particular classroom contexts. Without prior knowledge of these exact contexts, one can only plan generalised actions which become modified through classroom practice. For example, student reflections were monitored throughout the study for heightened emotional responses. Working with abstract concepts, challenging misconceptions, practicing peer and self assessment and describing one's thinking processes can be difficult tasks when encountered for the first time by students. As discussed in the literature review, to avoid possible downshifting it was important, therefore, to identify those students who felt uncomfortable by the process and to take the appropriate steps to ensure that these same students were given enough time to absorb the science curriculum and complete the given tasks. An adequate degree of teacher facilitation, and in some cases intervention, had to occur in order to decrease tensions and stressful emotions. Students were given many opportunities to voice their opinions and concerns throughout the study in the journal entries. Laboratory group members were chosen to include students with a variety of ability and motivation levels, as well as those who respected each other and worked well together. Peer assessment was done anonymously and the choices for peer evaluation were made with specific intents in mind. In general, higher level students evaluated mid to lower end students with the underlying assumption that their analytical abilities would allow them to point out areas that other students would miss. Lower end students were given samples of higher quality, to allow them to examine and learn from the work being assessed. The variety of student abilities found in the classroom would be used to help each other to develop deeper understandings of scientific inquiry.

The laboratory investigations were specifically chosen over a time period of five months so that they could be sequentially developed with progressive degrees of difficulty. This was done, in keeping with the reviewed literature, to promote a rehearsal of scientific process skills that allowed students to reinforce their prior knowledge, build upon it with increasingly abstract and counter-intuitive concepts and transfer their knowledge to other contexts. The degree of difficulty within the investigations themselves increased over time as students developed and questioned their own designs and hypotheses. All students were required to examine their results in terms of an evaluativist approach to scientific inquiry using hypothetico-deductive reasoning and critical thinking. Within their conclusion students were asked not only to explain their observations, but to relate back to their hypotheses, identify possible sources of error, explain discrepant results, suggest alternative designs for the experiment and examine further questions for inquiry. Laboratory groups were kept stable so that students could develop a rapport of trust with each other. Both small and large group discussions occurred before students were asked to communicate their knowledge in writing. Evidence of critical thinking and hypothetico-deductive reasoning was not systematically tested for at this time. Instead, student investigative written work was examined and compared using the established definitions constructed by students and myself in the classroom during the rubric construction process. The ability of the students to develop an evaluativist approach to scientific inquiry was based upon my own perception of the work itself, the students' abilities to critically assess the work of their peers and the perceptions of the students of their own progress and understanding of scientific inquiry as they worked with the rubric over time.

In order to establish confirmability, all of the data collected during the study was compiled in a complete file, with records of the verbatim transcriptions and their validations, teacher field notes and reflective logs and student work and metacognitive journals strictly maintained throughout. Many forms of the data were collected through triangulation, in order to provide an appropriate degree of credibility and trustworthiness. Participants were given opportunities to review and clarify their perceptions and describe their experiences first hand through both verbal and written means. The findings relate to the reality experienced by the participants in so far as the detailed descriptions mirror the perspectives documented at the time of the situation.

Following data collection, the data gathered through student experimental work, student learning logs, student self and peer assessments and the individual and group collaborative rubrics were collected, organized and coded for similarities, differences and ongoing themes. The coding of student work was a lengthy process. Laboratory work was first evaluated by myself, in the role of a teacher, using the rubric. I then examined the peer assessment of this same work and compared each student's analysis with my own. After this, I went back to the original student and again compared their self-assessment with my own. I looked specifically for whether or not student perceptions about scientific analysis agreed with my assessment, and whether or not the rubric was a useful tool. I coded the students' reflective comments regarding the rubric itself to look for areas that worked well and changes that could be made. I highlighted the student work that I felt best demonstrated the critical points and themes discovered.

Categorization of the data into segments and subsequent summarization of these categories were written. When differences and similarities between the data gathered from the biology and chemistry classrooms were examined, certain patterns became clear, particularly concerning the importance of context and transferability. The final phase of the data analysis moved towards a more interpretive framework, and included a more holistic perspective. Relationships and conclusions were drawn from this analysis, with meaning attached to the identified themes.

Delimitations

Several delimitations were intentionally implemented in the study. The teacher participant selected to partake was chosen based on his prior experience with student-generated rubrics, and his overall expertise in the area of assessment. The fact that he was not a science educator was also relevant, as it attests to the value of the pedagogical approach across disciplinary boundaries. This study was not intended to be a representative sample of all grade 11 students taking science, although I would like to transfer this pedagogical approach to other science classes at other age levels and other schools in the future. Generalising to all science classrooms from my findings is not possible from such a small sample size. The experiences that these students have will be unique to them. This study was delimited in terms of the amount of time that data could be gathered, as all classes researched were semesterised over five months. Students were not asked to participate until a firm basis of trust had been established in the classrooms. Data gathering was brought to a close before the last month of each course, as students were focused on preparing for their final exams. The number of classes chosen for the study was dependent upon the appropriateness of the courses and the teaching schedule assigned to me by my administration.

The action research study was not designed to provide a recipe for initiating the incorporation of student-generated rubrics in science classrooms. It explored the effects of opening up the assessment parameters in science to include students, and the subsequent changes in those students' perceptions of their work. The validity of the findings presented can only be judged by the reader on the basis of descriptive evidence. Each classroom context is unique enough to demonstrate that different factors exist when the approach is replicated. Reliability, in terms of repeatability, will not be claimed, as these factors are too diverse in nature.

Limitations

Several limitations inherit to the study existed. A framework of trust had to be established prior to the interviews. Interviews were only conducted once a rapport was established. Because I requested interviews from students who held strong opinions and had shown themselves to be motivated learners, student reactions are not assumed to represent reactions held by all students in my class, nor is it assumed that they reflect a cross section of opinions that students would hold in other similar classes. Teacher influence must also be considered. The interview participants were provided with the interview questions in advance to help focus the conversations. Teacher and student opinions changed dramatically as the study progressed. A stressful teaching day or a low mark on an assignment could affect how teacher and students perceive the process. As such, it is important to note that interviews are merely single representations in the overall experiences of the participants. Student responses are affected by many factors, including their relationship with the teacher. Difficulties of acting as both teacher and researcher require that a claim of objective-observer for this study cannot be made.

Class sizes are determined by the administration rather than the teacher, and thus a discrepancy existed between the sizes of the chemistry and biology classes involved. As well, the structure of the timetable and the curriculum influences the manner in which courses are taught. The chemistry courses were taught in a semestered school every day for 62 minutes over a period of five months. Once a week, two chemistry classes were given back to back. This double class allowed time and opportunity for more in-depth laboratory investigation and discussion. The biology classes, taught at a different school, were also semestered, having classes every day for 80 minutes, but without the weekly double class. Most of the discussions in the biology classroom were limited to a single class.

Assumptions

Many initial assumptions were made before carrying out the study, based on the choice of participants and my belief regarding assessment. The requirement for both Chemistry 20 and Biology 20 is a passing grade of 50 percent in Science 10. At this level of high school, the students are able to choose the types of science courses they take, and often the choices made are based on aptitude, interest and post-secondary requirements. These students are typically academically-oriented and are generally highly motivated to do well. This type of classroom environment was thought to be preferable because motivation is important in establishing student authenticity during rubric formation. The eleventh grade was chosen for this study because courses taken are not Diploma-based, where the students tend to be focused on standardized test outcomes. As well, with reference to the literature reviewed, the students are at an age when constructivist teaching of science inquiry, higher level understandings of abstract concepts and metacognitive reflection may be most appropriate.

This study is based on the premise that student assessment in science can be improved when students begin to internalise learning outcomes. This internalisation process can be promoted when students are involved in the construction of the assessment tool. Improvement in assessment, in this context, does not relate to improving standardized test scores or correlating teacher assigned grades with those achieved on standardised tests. Meaningful understanding of quality work should be agreed upon from the perspective of both the student and the teacher.

Ethical considerations

The practitioner must always be aware that he or she holds a position of power and this involves certain obligations and responsibilities to ensure that students are not put at risk. A certain degree of conscious proactiveness had to be inherent in the revised planning stages of the research to ensure that the needs of the students were being met, specifically in terms of the skill level required and the metacognitive expectations of the assigned work. In action research, the nature of the problems investigated and the methodology used must be mutually agreed upon by the research group. A written outline of the purpose and methodology of the research was prepared for the teachers, students and parents of the students who were involved in the interview and action research. I also explained the purpose of the study orally to the teacher and student participants when I sought their participation. All participants were required to sign informed consent forms and all minors required parental permission. If a student was not inclined to participate, regardless of parental permission, I would not have included their work in the study. Any student wishing to decline having their work used had the option to withdraw at any time from the study (but not from the course) without consequence. Teachers and parents could contact myself for further information or clarification at any time. The research proposal was fully explained and supplied to my school administrators prior to the commencement of the study.

During the student interview process I made clear beforehand that the students were not obligated to do the interview, and that their responses would in no way affect their grades in my class. I stressed the fact that participation was voluntary, and over and beyond what was expected of them as students in my classroom. Finally, I also ensured that the students were aware that all research data collected would remain confidential and that they would not be identified in any way. Students could seek clarification to any of their questions prior to, during, or following their interviews. All interview participants reviewed a transcribed copy of the discussions and were able to add, delete or change the content as deemed necessary.

Transcripts and any student work used in the study will maintain the anonymity of the participants involved, with pseudonyms appearing throughout this thesis. All data and summaries gathered will be retained in a secure location for a period of five years, following the study. After this designated time period, all data will be destroyed. I received approval for this study from the Faculty of Education Research Ethics Review Committee, and from the appropriate school district after filling out the relevant Cooperative Activities Program forms.

Chapter IV: Research Findings

Overview

This chapter provides a closer look at the evolution of the two research spirals that emerged concurrently throughout the study. The research findings described here will follow the sequence of events documented through my own field notes, student work, written student reflections, audio taped small group student discussions and student interviews. The initial interview with my colleague concerning rubric generation began the study and provided insights into how to set the stage for classroom action. The spirals that resulted followed a chronology of planned action, but the time lines in each of the classroom environments documented differed. The majority of the data collected is from the later Biology 20 classroom, however student work and reflections will be included from the Chemistry 20 classrooms as well. Events unique to these classrooms are explored to provide a context for understanding the importance of motivation, cognitive abilities and prior experiences in science.

Setting the Stage for Classroom Action

Prior to beginning the research in the classroom, an initial inquiry was made into the current literature surrounding theories about science learning, rubric formation and metacognition. My interest in these topics stemmed from conversations I had had with an English teacher who was using student-generated rubrics for essay construction and written language composition assignments in his high school classes. Process skills are those that are repeatedly developed over time in a particular discipline and can be applied to a variety of contexts. Scientific process skills are developed in science classes to provide students with hands on experiences with the natural world. The underlying assumption behind doing an experiment in the classroom is that the students will make connections between what they are observing and the curriculum of study. Meaningful facilitation of science process skills in the classroom can also provide a deeper understanding of the nature of science and scientific inquiry, develop critical thinking skills within an evaluativist framework and give opportunities to challenge common misconceptions in science. Science process skill development can present a unifying thread across the science curriculum and between different science disciplines. In order for any pedagogy to accomplish these goals, students must be actively and affectively involved. If we want students to understand and apply what they have learned, they themselves must recognize the value of the classroom tasks assigned to them. My colleague's prior experiences with student-generated rubrics and process skill assessment provided valuable insights into how to effectively implement scientific inquiry and teach science process skills in my classroom.

Interview with Colleague

During the semi-structured interview, my colleague explained that he only utilizes rubrics at very specific times and reasons. In his classroom, he limits their use to long term and year long activities. A rubric is given out at the beginning of the year and returned to regularly. Students are expected to internalise both the standards and the criteria of the rubric. In the interview he stated that, "Ultimately, the kids need to be able to generate, be able to internalise and apply those criteria on a regular basis." Rubrics can help to demonstrate conceptual understandings and transference. This occurs when a concept is still adhered to even though it is being applied to a new and different situation. In his words:

> A rubric looks at conceptual understanding and the big learnings, not the little stuff. I don't see rubrics as a vehicle of giving feedback, but rather as a vehicle of giving direction up front. Your feedback as a teacher is certainly related to the direction that you gave, but the rubric identifies where we are going, not so much where we have been. If it is an ongoing concept that goes through your entire year the rubric remains the same but the material you are working with becomes more and more complex. The process remains the same,

> the goals remain the same, but now you are adding different and more complex tasks. The process is developmental and task related.

The function of the rubric was further identified as a metacognitive vehicle, such that it provided a process by which internalization of the standards and ownership of learning becomes the responsibility of the students. The teacher interviewed stated, "The kids have to own their own learning. To do this you have to be able to say, at a very basic level, 'Here is where I am, here is where I want to go, now how do I figure out how to get there?'". In light of the ideas expressed in the interview, use of a rubric to develop critical thinking skills, hypothetico-deductive reasoning and the rehearsal and application of science process skills to increasingly complex and novel experimental situations would seem to be an appropriate assessment tool for use in science classrooms.

During the interview, several benefits and hazards of using rubrics for assessment were outlined. He suggested that effective rubrics have specifically outlined criteria and a set number of identified standards. Ideally, they make the teacher clear in terms of criteria and standards of what he or she is expecting and this should be explained to the students in advance of handing in the assignment, rather than after the fact. Specifically, my colleague felt that, "You still have to make sure that the kids are very clear on where it is that you are expecting to take them and what it is you are expecting them to demonstrate in terms of their understandings." Often rubrics are constructed with very minimal deviations in the standards. This makes it difficult for the teacher to reasonably evaluate student work. Clear differences must be set out in order for both students and teacher to understand differences in quality. Another problem concerns the number of different criteria outlined for a particular task. Rubrics that have too many criteria can be overwhelming and unmanageable. The teacher interviewee suggested that when too many criteria are constructed, rubrics end up being used for summative rather than formative assessment. Rubrics that are made to be descriptive in nature tend to have a lot of criteria. When rubrics are made to be prescriptive they can change behaviours and affect learning because they are providing something that is manageable and easily understood by the students. It was suggested that a thoroughly complex task should not have more than five criteria.

There must be a certain level of meta-understanding before students can be involved in the generation of a rubric. Students do not generate criteria; that is the responsibility of the teacher in agreement with the curriculum. Their role is in the identification of the different standards. According to my colleague, "Giving the kids, for example, models of well organised work, lesser organised work and poorly organised work and having them identify the differences in the standard of organisation and the necessary elements of organization, is the level at which I like to involve the kids." It is important that the criteria become part of the students' language and understanding first. According to this teacher, "Student-generated is really student-teacher-generated. The understanding of the entire process has to be there first." The students become involved in the process at the point at which new complexity is brought into the process. At this time, students should have a certain degree of familiarity with the tasks and they can begin to speculate about the standards. My colleague described this process:

> It is interesting when kids speculate, as typically they set higher standards than I would set, and that is immaturity, obviously, but once they have generated the rubric, and taken their own samples and evaluated them based on the rubric they have generated, they begin to see whether the evaluations are indeed accurate, if they fit, and then they can revise the rubric to fit.

The degree of teacher facilitation at this point depends upon the abilities of the students. Classrooms are heterogeneous mixtures of students and it is important that during the discussion of standards students arrive at their determinants together. For example, during discussion a more outspoken child may be speaking for a more reticent child. Deciding upon the participants in the student groups during the collaboration of the standards is very important. As well, students have to be at the level where they can fully understand the criteria. Students need to have a set of benchmarks that demonstrate differing degrees of proficiency and they need to be able to develop the process of identifying these same benchmarks for themselves.

It was suggested that students should individually generate the rubric standards before they met in small groups. These standards must be able to show the differences in proficiency in terms of the actions completed. Groups of three or four students are preferable because there must be ample opportunity to speak, listen and contribute. The group has to arrive at an agreed upon set of standards for a particular criterion. Once the compromise has been reached, it must also be articulated. There will be some degree of disagreement in the discussion and the consolidated standards will begin to change form. When all of the group rubric standards are collected, the teacher selects those that are the most appropriate and incorporates language from most of the groups into the rubric so that the students can see their own words amongst the collective voice.

A reflective metacognitive component was also suggested to be an important part of using the rubric to evaluate work. Through editing, evaluating and writing about the work, a student can come to an understanding of what it is he or she is trying to say, and this itself helps to formulate the thought process. During the interview, my colleague described the benefits of a reflective journal:

> Anytime you put something down you make it permanent. You are able to go back and revise your thinking. You can see what you have thought and you can see how you can go back and make changes to those thoughts.

When students reflect about past and present writing it opens the door not only to curricular metacognition, but also to a deeper personal understanding of cognition itself.

Designing the Planned Classroom Action

Based on the descriptions provided by the prior experiences of my colleague I subsequently initiated the sequence of action that would take place in the classroom. The research initially began in two Chemistry 20 classrooms at one high school and then moved to a Biology 20 classroom the next year at a different high school. Prior to beginning the research I had to make sure that I had gained entry in the selected schools in terms of familiarity with my colleagues, administration, student body and school environment. The research was performed during the second school semesters (February to May). The rubric generation process was initiated only after student familiarity with science process skills was established. Students were selected to work in groups of three and four, and these groups were maintained throughout the study. A maximum of five assessment criteria describing science process skills and four levels of proficiency were provided to the students. Each student was individually required to construct standards for the criteria based on his or her experience with an initial open-ended experiment. These standards were discussed within the groups and consolidated. As teacher, I then created the class rubric using the common ideas and language of the students. Based on the curriculum, subsequent experiments were performed which incorporated a sequential increase in complexity. A complete description and comparison of the planned action of investigations and rubric generation process between the chemistry and biology classrooms is provided in Appendix D.

The Action Research Spirals

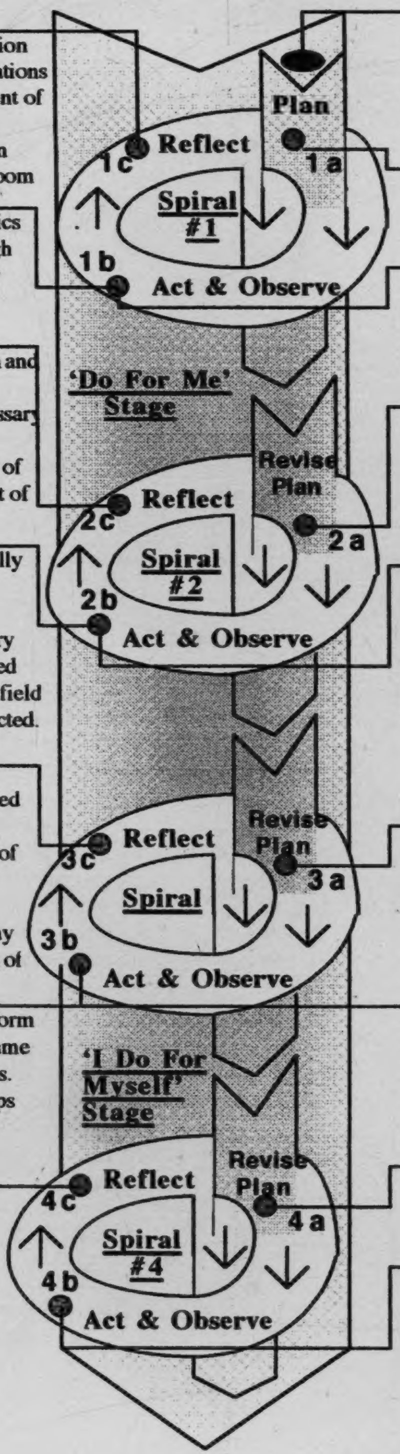
The following two figures summarise the emergent metacognitive and science process skills action research spirals that emerged in the study. The overall spirals are composed of the three stages of planned action, acting and observation of that action, and reflection of the process. Upon reflection within each of the individual classrooms, a revised plan of action occurred. Although the basic plans of action were similar in both the chemistry and biology classrooms, there were distinctive differences between them that had an effect on courses of action and the timelines followed. Each spiral within the classrooms informed the next in different ways. The four general sub-spirals occurred concurrently between the two figures. It is difficult to separate science process skills development from metacognitive development because they occurred at the same time and influenced each other throughout the study. The compiled data from each of the four sub-spirals will be described separately in the next sections. The classroom observations arose from my own teacher field notes and reflective journal and the responses from students given in their work and reflective journal entries.

The First Science Process Skills Research Spiral

A classroom understanding of scientific inquiry had to be in place before an initial experiment could be attempted. The amount of time spent on this introduction was affected by the science background of the students and their prior experiences with scientific inquiry. Most of the students in my chemistry classrooms had had ample experience doing experiments and writing about them. I had taught many of these same students in previous courses and they were already aware of how to compose an experimental write-up and of how to approach their conclusions using hypothetico-deductive reasoning. They understood the difference between a hypothesis and a prediction, were able to relate their findings back to their hypotheses and knew how to identify and account for sources of error in their designs. Generally speaking, these students were highly motivated and put a lot of effort into their work. Students that were new to the school, or had little experience with investigations, were assigned to groups with higher level students to promote discussion and peer feedback. As such, it took little time to create classroom definitions for science process skills in this kind of classroom context.

Figure 1: Science Process Skills Research Spiral

(adapted from Kemmis & McTaggart (1990))



1c: Extent of teacher facilitation determined based on interpretations of observations. Establishment of an environment conducive to scientific inquiry dependent on many factors related to classroom context.

1b: Initial classroom dynamics unfold. Data collected through teacher field notes and teacher journal.

2c: Further teacher reflection and interpretation of student understanding of criteria necessary to scientific inquiry. Comparison of actual quality of work with student assessment of that work.

2b: Students asked to critically analyse the presented experimental designs. Establishment of the necessary criteria for investigations based on class discussion. Teacher field notes and reflections are collected.

3c: Anonymous peer assessment partners are selected by the teacher based on an analysis of quality and effort of student work. The focus of this selection relates to assumed benefits students may encounter during comparison of work.

3b: Students design and perform a second experiment in the same previously established groups. Individual laboratory write-ups are handed in using the class-generated rubric standards.

4c: Teacher examination of compiled student work over time. Data analysis focuses on student understanding of the nature of scientific inquiry, demonstration of critical thinking and whether or not misconceptions are being challenged.

-Literature Review of learning in science, rubric formation and metacognition. Movement between schools and gaining entry.

1a: Initiation of class discussion on the mechanics of scientific inquiry.

1b: Observations of classroom environment and degree of the students' prior experience and levels of ability.

2a: Students in small groups are given an initial open-ended investigation, with no set parameters. Students present different designs and compare their methods.

2b: Misconceptions concerning science content arise and are addressed through group discussion and comparison of work. Individual student experimental work collected and assessed by the student and the teacher after a group peer evaluation.

3a: Critical evaluativist approach to scientific inquiry further developed through the rehearsal and application of science process skills to a novel and more abstract investigation.

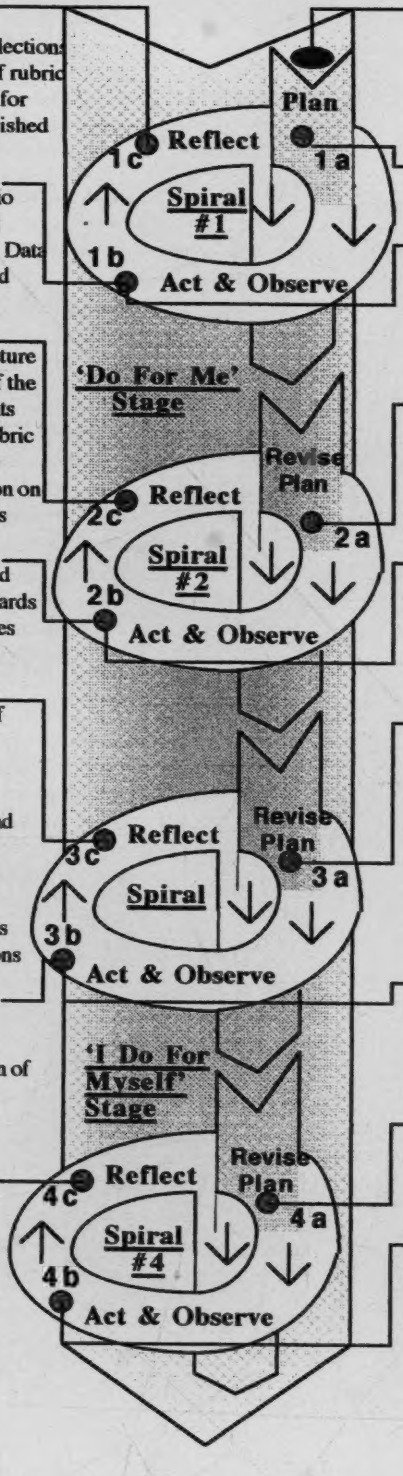
3b: Teacher analysis of the student work and establishment of the degrees of abilities. Teacher field notes and reflections are collected.

4a: Students asked to critically evaluate their work and the work of their peers using the rubric.

4b: Teacher evaluation of the second investigation using the rubric standards. Peer and self assessment by students of same work is compiled and compared in terms of perceptions of quality.

Figure 2: Metacognitive Research Spiral

(adapted from Kemmis & McTaggart (1990))



1c: Transcribed interview is validated. Field notes and reflections are interpreted. The basics of rubric generation and an appproach for classroom initiation is established based on discussions and reflections.

1b: Colleague interview audio taped and transcribed. Initial classroom dynamics unfold. Data collected through teacher field notes and teacher journal.

2c: Discussions about the nature of the rubric becomes part of the classroom language. Students metacognitively construct rubric standards in terms of actions completed. Teacher reflection on classroom context and factors limiting the experience.

2b: Classroom discussion and establishment of rubric standards of quality. Teacher field notes and reflections are collected.

3c: Student internalization of rubric standards through argumentation and collaboration. Audio taped discussions are transcribed and interpreted. Student group work is consolidated by the teacher into a class rubric standard. Student language is incorporated into the selections chosen.

3b: Small group student discussions (listening and expressing) and consolidation of rubric standards by students. Group consolidations are handed in to the teacher.

4c: Transcribed student interviews are validated and interpreted. Student work over time compiled in a portfolio. Teacher analysis of student work, student reflections, and field notes. Coding of data for commonalities and differences.

-Literature Review of learning in science, rubric formation and metacognition. Movement between schools and gaining entry.

1a: Creation of an atmosphere of trust, respect and familiarity in the classroom.

1b: Observations of classroom concerning the establishment of trust, how much time is required before process can begin and degree of student motivation.

2a: Classroom discussion to be initiated on rubric definitions and their use as an assessment tool. Student initial self and group peer assessment of presented work.

2b: Student work on the first experiment is presented, compared and assessed by the teacher, the student and the class as a whole.

3a: Most students reach a metacognitive level where they begin to articulate their thinking and actions. Rubric standards are first prepared individually by the students so that all may enter into the discussion. Appropriate group sizes and members are decided for rubric collaboration process.

3b: Two student group discussions are audio taped and transcribed. Teacher field notes and reflections are recorded.

4a: Generation of reflective student assignments involving rubric for peer and self assessment over time.

4b: Anonymous peer and self assessment of experiments using the rubric over time. Teacher examination of student work and comparison of perceptions of quality. Six student interviews audio taped and transcribed.

The experiences of the students in the biology classroom were somewhat different. The class of students was much smaller, having only 24 students as opposed to the 35 students present in each of the chemistry classrooms. This was beneficial as it allowed for much closer teacher contact with the students. In the first high school, a larger body of students allowed for a much more heterogeneous grouping. The second high school had a much smaller overall student population and as a result, the biology classroom tended to be composed of students that had taken similar options rather than being a random sampling. I found that these students' prior experiences with investigative science were extremely limited. In fact, for many of them, the initial discussion of the criteria for science process skill development was the first time they had ever encountered true scientific inquiry. Consequently, the research spiral for these students took a much longer time.

Other factors specific to the biology classroom related to discipline and maturity, which in turn effected the amount of effort and motivation of the students. Overall, these students had very weak skills in science, had poorly developed listening skills and had difficulty focusing on any given task. Some of the students were completely lacking in prerequisite science skills and would have been better placed in a different science stream. Four of the boys tended to be loud and attention-seeking, while most of the girls preferred to sit back and let others do the talking for them. All of these issues had to be dealt with before these students would be able to benefit from this type of pedagogical approach.

Upon reflection of the first science spiral in the chemistry classrooms, I felt that these students were ready to begin an open-ended chemistry experiment in small groups with little teacher instruction. For these students, excessive teacher facilitation at this point in time would have been somewhat obstructive to the trial and error approach students adopted upon being presented with a problem that lacked a specific procedure. This was not the case in the biology classroom. The introduction of an investigation with no set parameters and little teacher facilitation was not appropriate at this time. The revised plan of action for the next science spiral was modified to include much more specific teacher instructions and help with the science process as the biology students began to work within their small groups.

The First Metacognitive Research Spiral

Establishing an appropriate classroom atmosphere of trust, respect and familiarity was essential to this research. When students are asked to share their work with others and voice their opinions in group discussion, they need to feel that their voices are being heard and their work is being respected. The initial classroom discussions occurred in whole group settings that encouraged risk taking. All students were made accountable for not only their responses to questions, but also the way in which they responded to others in the class. Discipline was strictly adhered to and the students were given specific guidelines for their classroom behaviour. This attention to discipline was enforced repeatedly in the biology classroom until the students began to get a strong sense of the boundaries limiting their actions. My own experiences with discipline mirrored comments made during the teacher interview. My colleague stated,

> Part of this process has to be interlaced with discipline. I demand that the classroom be a place where we respect one another, in everything we say and do. For example, one expectation is absolute attention during presentational work. You don't shuffle papers, you aren't looking out the window and you aren't focusing on something else. A mindset must be set in motion that the classroom is a place where somebody is putting themselves on the line. That has to become part of the classroom procedure and then it can become an understanding classroom where the kids empathise with one another. Once that is in place then everything else fits in.

An important part of experimental work in science requires trusting one's group members, having a full understanding of laboratory safety procedures and being adequately prepared for investigations. All students were required to construct a written 'pre-lab' before being allowed to partake in any classroom experiments. As students began to work within these boundaries, they developed a familiarity with each other, the experimental process and themselves as learners of science. The classroom was defined as an area where students were expected to come prepared to learn science and over time, a general atmosphere of respect developed. This process took a few weeks in the chemistry classrooms and over a month in the biology classroom.

Throughout the study it became obvious that a strong affective component needed to be developed in the students in order for them to meaningfully benefit from the given tasks. Part of the struggle from a teacher's perspective, has to do with the incoming attitudes of the students towards school and the learning process. I classified the general attitudes of the students during the first two research spirals as the "Do For Me" stage. They had been trained by their previous school experiences to sit in the back of a class and take down notes passively. They were fabulous memorisers and regurgitators of information, but they did not value the learning process and did not actively construct their knowledge during class time. It was the easiest way for them to get by. The students had the attitude that responsibility for their learning rested on their teachers, not on themselves. There is little risk or challenge involved when the teacher does all the work in the classroom. In this study I learned that, in order for students to begin the subsequent metacognitive and science development spirals, we had to first address the difficulties of motivation, discipline, differing levels of science reasoning abilities and metacognitive awareness. Students had to want to learn and also begin to value the process of learning. The responsibility was challenging and frustrating; a classroom environment that is conducive for learning of this nature cannot happen overnight. As a teacher it is much easier and takes less of a time commitment to teach for content over conceptual understanding. In order for the pedagogy to be effective, students had to believe in its long term benefits for themselves as learners of science. Although a few students developed this type of attitude early on in the study, the majority progressed slowly through the spirals before they began to recognise the benefits for themselves. Most students had to experience the process and reflect upon it before they began to appreciate it. The less motivated students demonstrated little effort and never reached this understanding.

Prior experiences with the science process may have had an effect on the differences observed between the classrooms within this general spiral. For the chemistry students, a familiar atmosphere was easily established and moving into the subsequent spiral involving the rubric itself appeared to be a natural progression. Within the biology classroom, the move towards developing a process skill rubric had to be changed. The initial metacognitive spiral for these students was longer lasting in that many management and discipline issues had to be specifically dealt with first. As well, open-ended inquiry challenged many of these students strongly and it was felt that a period of whole class discussion re-examining the basis of scientific inquiry was required. It was important to not produce a negative connotation with classroom laboratory work in the minds of these students. To reduce any feelings of anxiety, it was stressed during the discussion that doing science was a learning process at which we were just beginning. Only when I had felt that the students had gained better insights into what they were doing and why they were doing it, did I feel the next metacognitive spiral could begin for the biology students. At this point in time, I revised my initial plan of action and gave the students rubrics from a previous class to examine before discussion began on developing a science process skill assessment tool. I felt that having more concrete examples of rubrics might help in their own formulations of what rubrics in science classrooms entailed. I was worried that by giving them rubric samples, it would have an effect upon their own individual future choices for the rubric criteria. At this point in the research, in order to establish an appropriate atmosphere of familiarity with science, I decided that this was was deemed to be the best course of revised action for these particular students.

The Second Science Process Skills Research Spiral

During the second spiral of the research we began to examine the scientific method, rubrics and sample work through an open-ended group investigation. The Chemistry 20 students were asked to create an experiment whereby they could observe a chemical reaction and discuss whether or not mass was conserved between the reactants and the products. Before the lab was performed, a discussion of the mechanics of the scientific method was carried out. Students were asked to get into groups of three and write out a problem, hypothesis, prediction and specific procedure for their experiment. Three different reactions were offered as possible testable entities and each lab group could then choose the reaction with which to work. Once the materials were chosen, students were given a series of classes to try out various ratios of chemical reactants, determine which ratio gave the desired amount of reaction and then measure the mass of the reactants and products to determine if mass had been conserved. Students could choose the materials to use and had access to others if they decided to make changes to their procedures throughout the class times provided. More than one group was assigned the same reaction, so that procedures could be later compared and evaluated between groups of students. During the experimentation process most students tried various approaches and made changes to their designs to try and create a closed environment. Without a set time line students were able to problem solve creatively. This appeared to increase their motivation and the level of discussion throughout the class. One student stated in her reflective journal:

> I really liked having the chance to create my own experiment. It made the lab much more fun to do. Usually we just follow directions from the book and doing labs is pretty boring. My whole group was totally into this lab and we felt good about ourselves for figuring out how to get the reaction to work. It took a long time to figure out but eventually we came up with a pretty good design. I wish more labs could be like this one.

The students observed in the chemistry classes were generally focused and actively engaged throughout the process. Through discussion of the differing experimental designs, many students felt that they gained a better understanding of their own work. One student described the benefit of the group comparison and discussion process in her reflective journal:

> I would never have realized all the different ways that mass could be lost in a chemical reaction! Here we were, carrying out our experiment, and we kept getting results that were way off from what we expected! At first we were pretty frustrated because we couldn't figure out why, but then we started brainstorming and thought about sources of error. For example, we hadn't considered any gases that might have been given off in the fume hood and weren't being measured. When we talked about this with the other groups, we found that one group's design was much better because they were trying to trap stray gases produced with an Erlenmeyer flask. We didn't even think about doing that. Talking it out was really useful. The better the design, the more accurate the results.

When the experiment had been carried out to the satisfaction of the students involved, each group was then required to specifically write down which changes they had made and why they had made them. At this point, students were asked to individually complete their initial lab write-up so that it included a graphical representation of their data, along with a conclusion which addressed an analysis of the results and possible sources of error arising from their experimental design. When the write-ups were completed, the groups that performed the same reaction were then asked to compare results with each other and determine which design was the most effective. In some cases, a combination of procedures provided the best design. During the discussion process misconceptions regarding the loss or gain of mass in chemical reactions were peer-addressed and possible explanations in terms of experimental design flaws were acknowledged. Finally, after this dialogue, students were asked to revise their write-ups to include the new design, address misconceptions and provide further possibilities for experimentation. This work was then teacher-evaluated.

In general, I found that the students expressed a lot of anxiety with this approach to laboratory work because of its indeterminate nature. Without having specific instructions to follow, they were continually questioning themselves as to the accuracy of their findings. One student wrote of the experience:

> I didn't enjoy doing this lab at all. It was really hard and we couldn't get it to work. Then we found out from the other groups that they couldn't get it to work either. What's the point of doing a lab if it doesn't work? I know you're trying to get us to think, but it would be easier if we had a set procedure to go by. All we learned here is that mass is conserved, but only if you control just about everything in the experiment.

Despite being unhappy about not having any set parameters to follow, this student still arrived at a fuller understanding of the nature of science. There are no set answers for true investigations but by controlling the environment one can minimise experimental design flaws. The quality of the student work varied for this investigation, but the self-reflective nature of the conclusion often lead to communication of higher levels of reasoning in the revised work of students that had put effort into the assignment.

When this second spiral was carried out in the biology classroom, similar student development was observed. In this classroom, students were required to design a thought experiment for disproving the theory of abiogenesis using cheese and the growth of mold. Each group was required to present their ideas to the class as a whole. Through class discussion, the most effective designs were determined to be those which included a vacuum, a sterilization process and a control cheese for comparison. Without being given any set guidelines to follow the students were able to present very different designs. This encouraged creativity and independent thought, as students demonstrated to each other that there were many different ways to demonstrate where the mold growth originated. An interesting class discussion emerged on the nature of different forms of data collection as a result of presentation work. One particular group differed from the rest of the class because their design first involved tracking mold growth with pictures and descriptions and then graphing these changes over time. An in-depth student-generated class dialogue occurred which centred around the difference between qualitative and quantitative data representation. For these students, similarly to the experiences observed in the previous classrooms, it would appear that peer discussion using a specific example can promote an increased awareness of scientific inquiry and the nature of science itself.

When work of varying quality was modeled to the students, they were able to understand and determine for themselves the necessary criteria of an experimental design and, within those criteria, which standards represented differences in quality. For example, when the biology students were asked to name the design they felt was the best and describe why, 19 out of the 24 students agreed upon the top design and were able to specifically articulate their reasons. Many of the student responses used their own work as a comparison to demonstrate why their top choice was selected. One student wrote:

> I felt that the best experimental design belonged to the group that included the graph and the microscope pictures as part of their results. They had a lot of detail, and I think that is important, because if you just say, 'the mold grew bigger', you're not really showing that. It's like an opinion. But if you show lots of measurements over a long time then you can really prove it happens. I also like the fact that they used a vacuum seal rather than just a jar with mesh covering that we used with the cheese. Since bacteria are so small, they probably could get through our mesh. In our experiment we basically didn't prove that life comes from other life. When we first presented it, we thought our experiment was really good. But after seeing the other procedures we realized that all we did was show that the life came from the air (which still isn't living) rather than bacteria. We needed a vacuum like the best group had.

By comparing her design to others, this student was able to independently identify not only the flaws in her procedure, but also to connect to the common misconception that life can spontaneously arise from the atmosphere. The work that was modeled and discussed in class was used by this student to address this misconception and come to a fuller understanding of how an experimental design can demonstrate the Cell Theory.

Although not all students were able to reach this level of understanding, the large majority of them were able to establish for themselves quality work in science.

By incorporating a presentation component to the experiment in the biology classroom, I felt an added dimension was brought to the process. The chemistry students only discussed their designs in small groups and did not engage in a whole class discussion. Teacher facilitation was brought into the biology classroom to a higher degree in that I asked specific questions of the students as they presented their designs. As a result, the class discussion was focused on addressing specific points and this in turn lead to more specific student comments when addressing their own work. The added teacher facilitation was thought to be required more for the biology students because their level of experience with scientific inquiry was much less than that of the chemistry students.

Similarly to those comments expressed by some of the less experienced chemistry students, many of the biology students felt frustration with open-ended science experimentation. There was no one way to do the science, and they continually wanted help finding the "right" answer. This is illustrated in the following student's initial self-analysis of how he could improve his work:

> The ways that I can improve on my lab work is to study the problem, know what I am asked to look for and strive to find the correct answer. For my conclusions I will try to make them longer. I have trouble with the conclusion because I don't know what the lab is about or I don't know what to say at the end when all the answers have been given to you in the results.

This student experienced difficulty with open-ended science designs because there is no obvious right or wrong approach. He mistook quality work with the quantity of words used and could not distinguish between an observation and a scientific explanation.

From a teaching perspective, the difficulty with introducing scientific inquiry in this manner is the amount of class time required. The chemistry students had to be given time to modify and try out alternate procedures. The biology students were given class time for the presentation and subsequent class discussion. Students must have a clear understanding of the mechanics of scientific inquiry before they can be involved in developing the rubric. A long term approach and a belief in the value of the process is required on the part of the teacher. The extended time required for this initial experiment benefits the students in the long run because these same process skills are repeatedly applied over the course of the semester. Internalisation requires active engagement. Designing the procedures and discussing their value with peers required a higher level of involvement from all of the students. This in turn promoted deeper understandings of the concepts, as articulated in both the modified conclusions written by the students and their reflective comments about the process itself.

Reflection upon the second science research spiral was required to inform the third spiral plan of action. For the chemistry classrooms, the students appeared on the whole to be motivated by the initial experiment. They enjoyed experimenting with various quantities of reactants and did not appear to be apprehensive about not having clear outcomes or challenging their conceptions about mass conservation. They questioned each other's procedures for validity and had little difficulty addressing their own procedural weaknesses upon group discussion. Little teacher facilitation was required at this point, and the next experimental design chosen for these students specifically involved higher application and rehearsal of their process skills, rather than repetition. Upon reflection of the abilities of the biology students after their first open-ended experiment, it was felt that certain students required more one-on-one teacher instruction on the nature of scientific inquiry. The process differed greatly from the chemistry classrooms, in that I extended the experience to include group presentations and whole class discussion on each of the group designs. A greater degree of teacher feedback was given for this group based on their weaker scientific reasoning abilities. More time was spent analysing and comparing between the groups in order for the biology students to reach a higher level of understanding of the basics of scientific inquiry. As well, the subsequent osmosis experiment chosen for these students in the next science spiral was open to a greater degree of possible student conceptual misunderstanding. I therefore spent a large amount of time working with the students outside of the laboratory establishing the initial scientific underlying hypothesis before initiating the next laboratory experience.

The Second Metacognitive Research Spiral

During the second metacognitive research spiral, students were asked to use the ideas they had generated from their comparisons of experimental designs and subsequent laboratory write-ups and construct standards of quality using a rubric template with a set number of teacher-derived criteria: scientific methodology, scientific content, presentation of data, hypothetico-deductive reasoning, and communication and organization. Each of these headings were defined through previous whole class discussion and had been firmly established as part of the classroom language. Students were required to provide a gradient of proficiency for their standards based on four categories of quality: strong, proficient, basic/emerging and weak/incomplete. The rubric template that was given to the students to individually fill in can be found in Appendix E. As discussed during the teacher interview, it was felt that students should determine the standards for the rubric individually. In order to be able to have an equal contribution of students during the consolidation of the rubric, it was necessary that all students were prepared ahead of the discussion time with their own ideas.

The quality of ideas expressed in the individual rubrics for the two chemistry classrooms was of a high standard. Students from these classrooms were able to articulate, using very specific language, which actions had to be demonstrated for each of the rubric criteria. For example, in the scientific methodology section, many students clearly differentiated between a hypothesis and a prediction and asked for a specific number of controls for each category of quality. The hypothetico-deductive reasoning heading often contained standards which were consistent with an evaluativist approach to scientific inquiry. A repeated standard in many of the rubrics for this section included statements linking the results to the hypothesis, a required number of sources of error and an explanation for discrepant results. The assignment was completed fully by all of the students at this time. It was clear that these students had an adequate background in scientific inquiry and were able to independently describe standards of quality. Many of the expressed ideas were similar amongst the students. As a result of having a large amount of previous experiences with investigative science, many students had already internalised the basic standards for the development of science process skills.

When selecting for group members in the consolidation process I first examined the individually constructed rubrics and then picked students with different ideas as group partners, with the hope of increasing the degree of argumentation when trying to reach a group consensus. It was felt that having three students work together, whose ideas were similar, would decrease the amount of discussion. I also selected students that had constructed vague and general standards to go with others that had more specific descriptions of action. This was done in the hopes of increasing the awareness and understanding of the weaker students of the importance of clearly defining demonstrations of learning in the rubric. The degree of motivation was extremely high with these groups of students, as demonstrated by the amount of effort that was put into the assignment. Students already demonstrating such a high level of ability in their understanding of science process skills may benefit more from rubric-generation strategies earlier on in their classroom science experience. For these students, this process could easily be begun in the ninth or tenth grades.

The experiences of the biology students were very different from the chemistry students at this stage. The level of motivation and effort was very low with this class. Many of the students had not adequately completed the assignment and were asked to redo their work. I felt strongly that all students had to be ready with ideas of their own before I would allow the rubric to be consolidated in groups. Students from this class were able to independently come up with only one or two standards for each criterion. Many of the standards given were vague to the point of being meaningless. For example, under the heading of scientific content, many students used words such as 'lab is specific', or 'content is good'. Under the same heading, the chemistry students differentiated this section into standards of terminology, clear descriptions of the concepts and explanations of the results with the investigative problem. At this point, it was clear that although there were some students with a full understanding of scientific inquiry, many of the students in the biology classroom were not able to articulate their understandings of science process skills in meaningful ways. When asked specifically about their abiogenesis laboratory designs, they could easily discuss particular ideas, but the transference of these ideas to a larger context was difficult.

Increased teacher facilitation was required to help lead students into a more specific expression of ideas. A whole class discussion occurred at this time, where the criteria were again described. I wrote specific comments on the individual rubrics and asked students to describe what they meant by using specific actions. For example, under the presentation of data section, I asked one student who had written 'Does good microscope drawings' as a standard, what he meant by, 'good'. At this point he was able to verbally describe specific points that he felt were important, such as labels, and correctly calculated formulas of scale. Once these students were given a second try at writing out the standards they became more specific. The majority of these students were not at the level of understanding of scientific inquiry typically represented in a grade 11 academic science course. Their previous experiences in Science 10 did not adequately prepare them for investigative laboratory work and their pre-requisite understandings of basic science concepts were weak.

Although my assumptions regarding the type of student I would have in this classroom were not correct, the potential of this pedagogy to change the lives of these students was much greater because they were at a level where these experiences could have a greater impact on not only their science skill development, but also on their awareness of themselves as learners. After observing these students working through the Biology 20 course, it became obvious to me that it is essential to meet the students at the level at which they are currently working, both metacognitively and with respect to understandings of the science content. For the purposes of this study and with the responsibility inherent in myself as their teacher, this meant I needed to allow the students more time with their assignments and to include more teacher feedback and facilitation with their work and peer discussions. The lack of motivation from many of the students was linked to their understanding of science, rather than a lack of effort.

Once the biology students had constructed rubric standards that I felt met an appropriate level of understanding, I carefully selected group members. Each group that was composed had a stronger student, two average students and one weaker student. I also ensured that outspoken students did not take over the group dialogue and encouraged shy students to participate. Each student was given a participatory mark and this helped to ensure that all students were involved in discussions. Three students did not take part in the group discussions because they had not completed the individual assignment. These three students completed the assignment during the group discussions and their ideas were incorporated into the class standard.

When constructing their individual rubric standards, the chemistry students did not have a problem expressing their ideas in their own language. The science literacy skills of these students were quite high. Understanding the purpose of a rubric as an assessment tool for science process skills was well understood and incorporated into the everyday classroom language easily. Upon examination of the students as individuals, I established group members for collaborative discussion. For these groups of students, I ensured that ESL students were placed with students that had higher literacy skills in science. The period of reflection for this metacognitive spiral required much more time and effort on my part as teacher for the biology classroom. Because the majority of students had difficulty with science literacy, the selection of group members involved taking into consideration motivation, discipline and degrees of ability. Students had to feel comfortable enough with each other that they would open up and be willing to engage themselves in the process. The emotional impact of this type of pedagogical approach on the students had to be carefully examined. I tried to ensure that the collaborative group members chosen would benefit each student. The teacher decisions made at the end of this metacognitive spiral had large impacts on the way in which the subsequent plan of action for the third metacognitive spiral was carried out by the students.

The Third Science Process Skills Research Spiral

When we had reached a point where a new level of complexity was involved in the experimental process, it was time to begin the third spiral of the research. A critical evaluativist approach to scientific inquiry was further developed at this time. For the chemistry classrooms, the investigation focused on identifying elements and compounds through the application of heat. The experiment was set up to specifically address the difficulties of a generalized procedure, an open system where products are lost to the environment, assumptions involving quantitative measurements and the limitations of using heat to break chemical bonds. The experimental design contained a few of the same flaws experienced previously, but within a different context. The critical approach developed in the first experiment would therefore be applied to a novel situation. After performing the investigation, the students submitted an experimental write-up using the class rubric as a guideline. This investigation marked the first time the students actively constructed an experimental write-up with specific learning outcomes in mind. The written work describing this investigation was examined by myself as teacher to determine which write-ups should be given to which student for anonymous peer evaluation with the class rubric.

In the biology classroom the second experiment was set up as a performance assessment assignment. The students were asked to design 'pre-labs' prior to performing the experiment that were read by myself before the students began the experiment. The students were required to develop a procedure for identifying three different solutions of various tonicity based on observed changes in the shape of onion cells viewed under the microscope. Students were assessed during the laboratory on their ability to use the microscope, their 'pre-labs' and their ability to answer a series of questions concerning the concept of osmosis and the designs of their investigations. Osmosis can be a counter-intuitive concept for students in that they often confuse changes in cellular shapes with the movement of solute rather than water. The performance assessment aspect of this investigation was used to ensure that all students were adequately motivated and were focused throughout. Upon circulating through the classroom I found that, although varying levels of ability still existed amongst the students, all had a basic understanding of how to construct an experimental design. Most of the students accounted for the variables and controls and had detailed hypotheses which included specific use of osmotic terminology. The language of scientific inquiry permeated the classroom and students generally remained on task. After observing these students, asking them individual questions and examining their 'pre-labs', I felt that this group of relatively weak students had reached a higher level of competency in scientific inquiry that was not present during the previous research spirals.

Student experimental write-ups were compiled after the completion of the investigation. I carefully examined the work at this time for evidence of misconceptions, misused variables, non-relevant controls and weak hypothetico-deductive reasoning skills. Student work considered by myself as teacher to be placed under the basic/emerging and weak/incomplete categories of quality were separated from the rest. Strong quality work was identified and also separated out. These stronger write-ups were assigned to the weaker students, while the weaker work was assigned to the stronger students in the hopes that peer feedback and comparison could benefit both types of students. Stronger students had to use a larger degree of analysis to be able to correct the misconceptions, suggest alternative controls and check for agreement between the observations given and the conclusions stated. Weaker students would be given work that would demonstrate to them the kinds of skills missing in their own work and give them a model upon which to improve. It was thus hoped that by specifically selecting the work for peer evaluation the process would account for differences in abilities among heterogeneous class groupings. My own perception of the quality of the work could then be compared to that of the students as evaluators. This comparison is described in subsequent sections of this chapter.

At the end of this third science research spiral a large reflective component was required on the part of myself as teacher. In order to inform the next and last science spiral, students had to be chosen for anonymous peer assessment following the rubric standards. The choices made affected the students' perceptions of their own work and therefore a strong emotional component was added to the process. Students had to feel comfortable with the anonymous peer assessment process, and be able to use the rubric at an appropriate skill level. Within the chemistry classrooms, I did not initially use secret names for the peer assessment. This turned out to be a mistake in that students were not comfortable knowing who examined their work, even though the students themselves were not being formally graded on this work. The biology students were given much more concrete instructions as to the kinds of specific analysis required of them during the peer assessment process. As well, student anonymity was established from the start. No one student was aware of whose work was being examined by whom. Thus the biology classroom experienced many differences from the chemistry classrooms in terms of the revisions made for the last science research spiral.

The Third Metacognitive Research Spiral

The third component of the metacognitive research spiral focused on generation of the class rubric. This was designed to offer students the opportunity to construct an assessment tool specifically fit to their needs. They used the criteria set out by myself as the teacher and used their own experiences from writing and evaluating experimental designs, to individually, and then collaboratively, develop the rubric standards. The process of argumentation and consolidation required the students to think about what was important to them when they wrote about scientific experiments. That in itself was a tremendous metacognitive experience. For the purposes of clarification, rubric criteria selected by students during the audio taped small group discussions will be italicised in the following quotations. This group of students from the biology classroom were able to move from a superficial conversation concerning the number of controls laboratory work should include to a more complex discussion concerning their relevancy by relating to work done in the past:

> Jeannette: How about sources of error?
>
> Jane: Ok, but how many?
>
> Jackie: I think at least four.
>
> Jeannette: How about putting *Controls were not all present*, or completely there?
>
> Jackie: Or something using general, the controls were too general. *Controls were not elaborated.* You know, how you can say like pressure was a control, even though the lab had nothing to do with pressure at all, or just say contamination was a control, instead of saying using a different or clean test tube for each test.
>
> Jeannette: Yes, or something, like, *Does not recognize all controls*, because sometimes they can be missing

	some really important ones, like temperature.
Jane:	Ok, and then, *Forgot to keep control of an important part of the lab*, like if you forgot to keep temperature the same. So the controls are not being maintained.

There were some problems encountered at this stage of the research. Not all students collaborated equally. They needed to be at a metacognitive level where they could articulate what it is that they were doing. Having prepared their own individual rubrics first, they should have been ready to begin a discussion. Those who did not put effort into the process individually could not discuss ideas at the same level as those that had. Those students lacking a basic understanding of the necessary criteria were often frustrated and had limited input. Many students had difficulty constructing standards that were visible and shown in terms of completed actions. For those students who did not have many prior experiences with laboratory work, the process was often frustrating for them because of its novelty and the amount of work involved. By selecting specifically for more small heterogeneous groupings within the classroom population, I felt that the more experienced students had greater opportunity to help out the less experienced. This provided greater social feedback, which was much more effective than that generated by myself as teacher alone. This is demonstrated in this audio taped small group discussion in the biology classroom between a stronger student and a weaker student:

Jerry:	For presentation of data we should use *Observations are of very good quality.*
June:	But we have to be specific. What is *good quality*?
Jerry:	Do you have to make this so hard?
June:	But that doesn't say anything. It's not specific enough. How about *Uses detailed observations*? Then we can just go *General*, *No specific detail*, and *Missing*.

Some students merely recited back what they thought their teacher wanted to hear rather than what they actually thought. The rubric formation process requires a degree of motivation that may not be present in all students. Students that were not engaged in the process were quick to let the teacher, as expert, decide what is important. This was illustrated when these same two students were attempting to describe hypothetico-deductive reasoning skills:

Jerry: I don't get what that whole heading means.
I had no clue when I wrote stuff down.

June: I think it means what you put in the conclusion.
How you explain your results. That's what
the teacher said.

Ingrained ideas about the control of the teacher in assessment are difficult to change. In contrast, groups that were working at a higher level of metacognitive awareness were able to establish meaning based on collaborative discussion, without relating to teacher expectations. This group of biology students, discussing the same topic, came to a shared understanding by relying on their own ideas:

Jackie: What about *Supporting evidence*?

Jeannette: Yes. We can put *Good, Very good* for
supporting evidence, and *Results are accurate.*

Jacob: How about *Prediction relates back to results*,
or something like that?

Jackie: I put *Reasoning and meaning behind the
experiment.*

Jane: How about *Further exploration*?

Jacob: Or *Further research.*

Jackie: Further research? What does that mean?
Is that for strong?

Jacob: Isn't this just talking about what you got,
like your results?

Jeannette: This one is a good one. So let's put it in. *Extra research.*

Jacob: Let's do something for the conclusion.

Jeannette: *Data was clear and made sense*?

Jacob: Let's say something about the problem. Like you have either solved the question to the problem or not.

Jeannette: Answer the problem. *The question in the problem was fully answered*, like that.

Jane: Ok, these are good for hypothetico-deductive reasoning

For this group, hypothetico-deductive reasoning was more than just a listing back of results. They were engaged in a give and take conversation that explored what experimental results meant to them as a group. Discussions of this caliber helped to move the students towards deeper personal understandings of the science process. The degree of teacher input at this stage differs depending upon the willingness of the students to take over and engage themselves in the process.

Rubrics that used categories rather than concrete number grades bothered many of the students during the peer assessment process. This was articulated in all three classrooms within some of the student journals, as well as during one of the biology student interview sessions. Having been used to a school environment that focused on a number value for a grade, assessing work using categories of proficiency caused concern among many students. Weaker students tended to focus on the superficial elements of the scientific method itself rather than examining aspects of independent analysis, relevant controls, and the search for discrepancies and sources of error within the design. For example, many of the students new to this process focused their rubric criteria on rewriting the procedure neatly and including all the materials and orderly data presentation, while ignoring the deeper connections related to the scientific concepts being examined in the experiments.

Once all of the groups had reached a consensus, the final rubrics were handed in and consolidated by the teacher. Those ideas that were represented consistently between the groups were incorporated into the class standards using student language. My own contribution to the rubric standards was minimal in the chemistry rubrics, as the students were able to come up with appropriate selections independently. Teacher input into the biology rubric was higher to ensure that the necessary curricular learning outcomes were being addressed. It is up to the teacher to decide the extent of his or her involvement based on the ability levels of the students. The final rubrics from these classrooms are presented in the tables on the following three pages.

The degree at which students were able to involve themselves in the process affected their ability to use the rubric in concrete ways. It was important, therefore, that the language reflected upon by myself as teacher for the rubric related specifically to the students that had constructed the standards. I also had to ensure that curricular goals regarding science process skill development were being reached by the rubrics. The chemistry students presented me with a variety of detailed standards to choose from. Many of the groups had similar ideas worded in different ways. I felt reasonably secure that the students understood the standards, related to the rubric constructed and were able to engage themselves fully in the last metacognitive research spiral. With the biology classroom, several of the individual rubrics were not completed. Many students in this classroom lacked the ability to write clearly about science process skills. Upon reflection, I revised the rubric construction process at this time. I gave initial written feedback to students concerning their initial individual standards, and asked several students to be more specific with their ideas. One student had mixed up the idea of presentational work with that of experimental. The biology students, therefore, required more time and clarification of their own personal ideas at this time. Although many new ideas were brought forth verbally during the discussion process, the number of different ideas written down by these groups was much more limited than that of the chemistry classrooms. The finalised rubric for this classroom had a much larger teacher input as a direct consequence. This rubric was gone over with the students in detail. The question arises as to whether this increased time spent on establishing the rubric helped or hindered student ownership within this particular classroom setting. The biology students spent more time working on the standards themselves, but not every group's ideas were represented in the finalised rubric itself. A revised plan of action for the next metacognitive spiral included much more detailed instructions for the biology students in terms of how they were required to reflect upon and analyse their own work and that of their peers, to ensure that they addressed all the criteria on the rubric.

The Fourth Science Process Skills Research Spiral

Peer and self evaluations using the rubric were performed with several subsequent investigations. Students were asked to write about their critical analysis skills and comment on areas that needed improvement. Students reflected about the evaluation process itself, their role as evaluators and their own evaluated write-up. All of the work done thus far was placed in a duotang so that students could look for patterns and examine their strengths and weaknesses. I gave the stronger work, written by the more experienced students, to the weaker students so that they could have a detailed, high quality example of an experimental write-up to examine. The strong students were given weaker work to evaluate in the hopes that they would develop their critical skills more fully and give a different perspective and helpful comments to the weaker students, based on their own experience with write-ups. The reflections given by the students provided me with honest feedback and a sense of the effectiveness of this pedagogical approach in developing meaningful learning experiences. The students gave valuable insights concerning their own progress, but also suggested specific improvements to the process itself.

A few of the higher level students from the chemistry classrooms expressed concern over their choice of peer evaluation in their reflections because they felt that they would have benefited more if they had had the chance to see higher rather than lower quality work for comparison to their own. One ESL student from one of the chemistry classrooms suggested in his reflection that having work to evaluate of high quality gave him a much better idea of how to write one himself. In general, the peer evaluations written by the students were very detailed and a lot of effort was spent in the examination of the work. Specific comments regarding examples, application and areas for improvement were present in the student evaluations. Students seemed genuinely concerned with helping their peers understand the concepts more fully. Having the evaluators graded on the basis of their analysis ensured that most of the students put a large amount of effort into their peer evaluations. Due to time constraints and large class sizes, it is more and more difficult for teachers to be able to adequately provide detailed feedback of student work. This process enabled each student to obtain a much more thorough look at his or her write-up while still in its initial stages of development. One biology student wrote:

> I liked having my work looked at three different times. At first I was unsure that having someone else look at my work would be fair, but the person who marked me did a really good job. They gave me a lot of specific comments and placed my work in the same category that I did - proficient. It was also good having the teacher look at the lab too because we might have missed some things. After all of us looked at this lab write-up, I had a pretty good idea of what I can do better.

When comparing my evaluation as teacher with the peer evaluations there was a high consistency from all three classrooms for deciding where to place the work in terms of its quality. Write-ups that I felt to be proficient were generally felt by the student evaluators to be proficient as well. Students had no difficulties identifying concrete standards relating to the mechanics of the scientific method, such as the number of

Table 1: Chemistry 20 Consolidated Class #1 Rubric

Assessment Criteria:	**Strong**	**Proficient**	**Basic/ Emerging**	**Weak/ Incomplete**
Scientific Methodology	-contains all components in the correct order -detailed hypothesis has background theory, and a specific prediction -correctly identifies variables and several relevant controls	-most components present in correct order -hypothesis and prediction are separate entities -variables correctly identified and a few controls given	-components missing and are not ordered correctly -hypothesis lacks content and prediction is too general -variables and controls incorrectly identified	-lacking in several components and a correct order -differences between hypothesis and prediction not clearly established -variables and controls missing
Scientific Content	-applies scientific theories/laws to the hypothesis -all relevant terminology is used and applied correctly -extra research helps to link concepts studied in class	-attempts to apply results to hypothesis are present -important terminology is used and applied correctly -extra research is present, but is not used to link concepts	-science explanation is basic and lacks full understanding -some terminology is used but not explained or applied correctly -extra research missing	-conclusion does not relate back to hypothesis -lists ideas but does not explain them -lacking in terminology -scientific misconceptions present -extra research missing
Presentation of Data	-detailed qualitative and quantitative observations present in charts -labeled graphs correctly represent data -accurate calculations with units and sig digs	-qualitative and quantitative observations present in charts -labeled graph represents data adequately -most calculations correctly done but lacking in shown work	-observations present but are not well organized -graph improperly labeled and misrepresents data -some calculations are incorrect or lack units, conversions or sig digs	-missing key observations -graphical representation of data missing -important calculations missing or incomplete
Hypothetico-Deductive Reasoning	-accurate conclusions relate back to hypothesis and actual results -independent scientific reasoning skills present -relevant sources of error, alternatives to design and further questions provided	-conclusions generally relate to hypothesis and results -some independent reasoning present -some sources of error, and an obvious alternative design provided	-correct conclusions given without analysis of data or full explanation -independent reasoning lacking -few sources of error present, weak attempt at a design change	-insufficient conclusion given based on the results -no independent reasoning present -sources or error are missing or not relevant, alternative design missing
Communication and Organization	-writing is neat or typed -spelling and grammar is virtually error-free -clarity of ideas presented is excellent	-writing is legible -spelling and grammar errors are minor and few -ideas are presented well	-writing is difficult to read and repetitive -spelling and grammar errors occur often -point form used -poor clarity of ideas	-writing is illegible and frustrating to read -spelling and grammar errors are frequent and obvious -few ideas presented

Table 2: Chemistry 20 Consolidated Class #2 Rubric

Assessment Criteria:	Strong	Proficient	Basic/ Emerging	Weak/ Incomplete
Scientific Methodology	-demonstrates all aspects of the scientific method in the correct order -clear definition between hypothesis and prediction -detailed summary of a procedure -recognizes variables and at least 4 controls	-most components present in correct order -hypothesis and prediction are distinguished -generalized procedure present -recognizes some relevant controls and variables	-components missing or lacking detail and are not ordered correctly -no differentiation between hypothesis and prediction -missing either variables or some relevant controls	-lab components are missing and not in the correct order -general theory missing and prediction is not specific -controls and variables not correctly recognized -lacking in effort
Scientific Content	-refers to scientific ideas and previous knowledge in the hypothesis -precise and accurate definitions applied -full understanding of concept demonstrated	-attempts to apply results to hypothesis and uses appropriate terminology -demonstrates understanding of concept, but not at a deep level	-some scientific misconceptions present -important concepts are not addressed, although some concepts are addressed at a satisfactory level	-conclusion does not relate back to hypothesis -shows no effort in understanding the concept -scientific inaccuracies and misconceptions are present
Presentation of Data	-qualitative and quantitative data presented in detail -charts and graphs correctly represent data -formulas applied correctly -accurate calculations with units and sig digs	-qualitative and quantitative observations presented in general -charts and graphs represent data adequately -most calculations correctly done	-observations present but are not well organized and lack specific detail -charts and graphs not well-organized -some calculations are incorrect, lacking in units, sig digs and proper conversions	-observations and data are inaccurate or missing important components -important calculations missing or incomplete
Hypothetico-Deductive Reasoning	-relates back to hypothesis and prediction in a meaningful way -demonstrates independent analytical thought -5 relevant sources of error discussed -improvements to procedure suggested -further questions for research and applications provided	-conclusions generally relate to hypothesis and results -some independent thought present -some sources of error, and an obvious alternative procedure provided -no further research or applications provided	-relation back to hypothesis is weak -no evidence of independent thought -few sources of error present, weak attempt at an improvement to procedure	-no reference to hypothesis -simply restates results rather than analysing them -scientific inaccuracies in data are not questioned
Communication and Organization	-neatly organized and easy to read -no spelling, grammatical or syntax errors present -precise, to the point, no fluff	-relatively well organized and neat -spelling, grammatical and syntax errors are minor -relatively focused and to the point	-writing is difficult to read -spelling and grammar errors occur often -ideas presented in a disorganized, choppy fashion	-unreadable and difficult to make sense of -poor spelling and incomplete sentences -unclear, rambling ideas

Table 3: Biology 20 Consolidated Class Rubric

Assessment Criteria:	**Strong**	**Proficient**	**Basic/ Emerging**	**Weak/ Incomplete**
Scientific Methodology	-demonstrates all lab components in the correct order -specific procedure given -correctly identifies variables and several relevant controls	-most lab components present in correct order -generalized procedure present -variables correctly identified and a few controls given	-lab components missing or lacking detail and are not ordered correctly -procedure missing some steps -missing some variables and controls or some incorrectly given	-lab components are missing and not in the correct order -procedure incomplete -controls and variables missing or incorrectly given
Scientific Content	-hypothesis depicts specific knowledge of subject and uses relevant terminology -specific prediction given -full understanding of concept demonstrated	-hypothesis generally relates to concepts and uses some appropriate terminology -general prediction given -demonstrates understanding of concept, but not at a deep level	-hypothesis is overly general and is lacking in important terminology -prediction does not specifically outline what will happen -important concepts are not addressed	-hypothesis is too general and is missing or uses incorrect terminology -no clear prediction given -shows no effort in understanding the concept and scientific inaccuracies are present
Presentation of Data	-lab drawings are correctly labeled -observations have specific detail -charts and graphs correctly represent data specifically -formulas applied correctly with accurate calculations and units	-lab drawings are generally present with only a few errors in labeling -observations are general but well organized -charts and graphs represent data adequately -most calculations correctly done	-lab drawings are present but not correctly labeled -observations present but are not well organized and lack specific detail -charts and graphs not well-organized -some calculations are incorrect, lacking in units and proper conversions	-lab drawings are incomplete and missing labels -observations are inaccurate or missing important components -charts and graphs incomplete or missing -important calculations missing or incomplete
Hypothetico-Deductive Reasoning	-conclusion relates back to hypothesis and prediction in a meaningful way -demonstrates analytical thought -many relevant sources of error and improvements to procedure suggested	-conclusion generally relates to hypothesis and results -some analytical thought present -some sources of error, and an obvious alternative procedure provided	-relation back to hypothesis is weak -no evidence of independent thought -few sources of error present, weak attempt at an improvement to procedure	-no reference to hypothesis -simply restates results rather than analysing them -no sources of error present -scientific inaccuracies in data are not questioned
Communication and Organization	-neatly organized and easy to read -no spelling or grammatical errors present -precise and focused -uses extra research with correct footnoting	-relatively well organized and neat -spelling and grammatical errors are minor -relatively focused and to the point -some extra research provided	-writing is difficult to read -spelling and grammatical errors occur often -ideas presented in a disorganized, choppy fashion -extra research is not correctly footnoted	-unreadable and difficult to make sense of -poor spelling and incomplete sentences -unclear, rambling ideas and lacking in effort -work may be copied or plagiarised

controls, the use of terminology or the organization of the work. There were more discrepancies between my perceptions of quality and that of the students for the science content and hypothetico-deductive reasoning criteria. Often misconceptions concerning the science behind the experiment were evident in the hypothesis and missed by the weaker student evaluators. Many students equated the length of the assignment with its quality of work. It was important, therefore, that each student was also given specific written teacher feedback for the same work. For example, this chemistry student wrote about his analysis of another student's work in his journal:

> When I looked at the person's work I realise now that I wasn't specific enough when I marked it. When I saw the comments you made on the lab I found that I had totally missed the fact that the person mixed up homogeneous mixtures with pure substances. A compound is not a homogeneous mixture and yet that's what it said in the hypothesis. My evaluation was good in that I explained to the person that they should have included more important controls like the amount of heat used and the time spent on decomposition, and the chart should have been better organized. I missed a lot of things in the conclusion. It didn't address some of the problems with the results and I didn't pay close enough attention to see if the observations agreed with what was said in the conclusion. I didn't notice that the person hadn't mentioned any other tests that could have been done on the gases. The Hydrogen pop test would have been a good idea. I guess it's because I missed these things on my lab or maybe it was because it was done on a computer and so it looked like the person knew what they were talking about.

The ability to critically evaluate experimental results is lacking in many students. With more experience over time, students can become increasingly aware of how to analyse scientific statements in terms of reported experimental results. This initial awareness was facilitated at this stage of the research through peer comparison of student work.

The majority of students used the rubric consistently and referred to specific standards when deciding upon the placement of the work. Some students were more aware of the concepts and had no difficulties spotting inconsistencies and correcting them in their assessments. For example, this biology student made the following written comments to another student in her evaluation of that student's work:

> You did a good job of using terminology in your hypothesis section. Be careful of using the definitions incorrectly. You are mixing up the fact that in osmosis it is water that is moving across the cell, and not solute. You are correct in describing what shapes each of the cells will have when they are put in the solutions, but your reasoning is not correct. Water moves from high to low concentrations, and the solute stays where it is. Good effort though.

This particular student decided that the evaluated work should be placed under the basic/emerging category because the science concepts were misrepresented. She was able to spot a common misconception concerning osmosis and corrected it for the student whose work was being assessed. There was a concern about assigning the placement, as demonstrated in her reflection journal entry:

> I had a really difficult time deciding where to place this lab on the rubric scale. I really felt bad giving the student a basic/emerging, because they put a lot of effort into it. But I kept coming back to the fact that the person totally mixed up in the explanation of why the cells change shape. Because the lab kept talking about solute and not water I didn't think it belonged in the proficient category. Especially since when I read the conclusion it just repeated the same thing all over again. I mean, if I had done that in my lab, I wouldn't have expected a placement above basic/emerging. But I still felt bad about giving it such a low placement.

When students took the role of evaluator it was evident that they felt a large degree of empathy with the student being assessed. This sometimes lead to evaluations that placed the work at a higher level than that chosen by myself when I evaluated the same work. Under the guise of analysing another's work objectively students often began relating to themselves. During the audio taped interview, this biology student described how the peer assessment process allowed her to come to an understanding of the quality of her own work:

> At first it made me uncomfortable, because my person was missing

> some things, and I felt bad. And that is when I realized the difference between strong and weak. But then it helped me because I figured out what my strong points were on my lab. He had some strong points that I didn't have too. Things I hadn't thought of until I read his lab. Things that for my next lab I could improve. It is like a learning process when you are correcting someone else's lab. When I corrected my person's work I pretty much compared his work to mine, and I noticed I used a lot more terminology, so I gave him a weaker mark because I thought mine was stronger. I think that looking at a stronger person's it would help too because I would find things that I missed and get other ideas. I would notice the components that were missing from my lab.

The perceptions of students towards their own work was often inconsistent with that of the teacher's assessment. Some student self-evaluations were judged more harshly than the peer-evaluations. Others gave their work higher placements than that perceived to be appropriate by the teacher. In general, student perceptions from all three classrooms of quality work were more in common with that of the teacher's when they marked each other, rather than themselves. The use of the rubric did however help increase students' awareness of how to write about their own experiments. This became evident as the students examined their work over time. At the beginning of the study and before the construction of the class rubric, biology students were asked to evaluate their abiogenesis write-ups. One weaker student wrote:

> I did some things good and some things bad. Our group did a good job of the procedure and our experiment worked really well. I need to put more in my conclusion and my handwriting is really messy. We forgot to put in variables and controls, so I need to remember to put them in next time.

This student did not have a clear grasp of the elements that make for quality write-ups. In this reflection, he gave vague descriptions of what he felt was good. He focused on missing elements and neatness for areas of improvement, rather than examining his procedure for specific design flaws or his conclusion for sources of error and possible alternative designs. He was unable to articulate about his work and his analysis lacked any demonstration of his understanding of scientific inquiry. After participating in the generation of the rubric standards and examining his work over a few months, the same student showed a remarkable change in his ability to meaningfully analyse his own work:

> I think my write-ups are much better now. I put a lot more effort into them and I have tried to address all of the points in the rubric. I figure I am at a proficient level now, whereas before I was only basic. When I write out the hypothesis, I go back to the notes and the book and I use terminology when I describe what the lab is about. I don't forget my variables and controls, and make sure that the ones I pick are specific to the lab. While I do the lab, I write out the things that might go wrong, so I can talk about them in the conclusion. I still miss things though. Sometimes when I get results that aren't quite right I forget to talk about them later. In the enzyme lab the test tube that should have given the largest reaction only gave a small one in our group. In my conclusion I explained why the test tube should have a large reaction, but didn't relate back to my actual results which didn't show this at all. I should have talked about our liver sample being smaller than all the rest, so the reaction wasn't as big. I think I have the hardest time with thinking of stuff like that, so I still need to work on my hypothetico-deductive reasoning section.

Working with the rubric standards allowed this student to use much more specific language when discussing his work. Instead of saying that his work was good, he explained how his work had improved in particular ways. He examined the level of his critical thinking skills and decided that this is an area he wished to improve upon in the future.

This biology student reflected on her past work and was able to articulate an awareness of her progress by applying what she had learned to a different context:

> My hypothesis in our osmosis lab was underdeveloped and missing some relevant information and terminology, as compared with my enzyme lab. Here, I specified more background information about what enzymes are and how they function. By being more specific in my hypothesis it helped to clarify my prediction by providing reasoning and logic.

It is important to note, however, that both of the above students demonstrated a willingness to improve upon their work. Reflections from less motivated students were often extremely general and did not relate to the rubric standards. The quality of the work performed by such students remained the same throughout the year. Students unwilling to put effort into their own work did not put effort into their self or peer evaluations either.

From both my perspective as teacher and the perspective of students in the class, the rubric has appeared to be an effective formative assessment tool for developing science process skills. Over time, motivated students from all three classrooms improved in their abilities to communicate their understanding of science concepts and began to make deeper connections that involved higher level reasoning abilities. They spotted inconsistencies with their work through peer assessment, acknowledged the relevance of experimental variables and controls and began to independently discuss their results in relation to sources of error and improvements to experimental design.

The Fourth Metacognitive Research Spiral

At this last phase of the study students were asked to write a series of reflective assignments which focused on their use of the rubric and their demonstration of learning over time. Students were given the chance to voice their opinions and to reflect on the assignments as a whole. During this research spiral, six students were chosen from the biology classroom to take part in individual semi-structured interviews concerning the rubric and their perceptions of the process. Having students write in a reflective journal was meant to promote metacognition and a sense of awareness of the quality of work being performed. Differentiating between the fourth science process skills research spiral and the metacognitive research spiral is important for the sake of clarity in describing the data collected, but it is important to note that because these spirals occurred concurrently, elements arising from one spiral impacted the other. The level at which students began to internalise the rubric standards for themselves was reflected in the changes observed in the quality of their work. Metacognitively aware students were able to articulate more clearly and perceived the greatest improvement from the entire process. Those students with poorly developed self awareness had difficulty using the standards to describe their work and the work of others. Evaluations from these students tended to use vague language and resulted in superficial assessments. Over time, students became more familiar with writing about themselves and thinking about their work as they wrote it. The metacognitive levels of the students varied by large degrees and the perceived and actual benefits to the students tended to mirror this level of awareness.

The specific feedback given by students had both intended and non-intended consequences. Several comments suggested that the majority of the students perceived a greater appreciation for their own learning. Many felt that they had a better idea of the quality of their own work as a result of comparing with others. In performing the initial open-ended experiments, the common idea that there is only one right answer in science was diminished because different perspectives were encountered that were scientifically valid. This understanding was present in many of the reflections. Examining a variety of ideas and being critically assessed by someone other than the teacher was suggested to be a more beneficial part of the process. Several students acknowledged that the peer evaluation was difficult to do because it made them pay closer attention to detail and they found this harder than actually doing and writing out the experimental work. Write-ups were often read and reread many times and students had to think carefully before putting their comments down on paper. The process appeared to have benefited two ESL students who expressed difficulties in evaluating but felt they received good examples of how an excellent lab is communicated. It was felt that the experience helped them in doing future assignments.

Students that became affectively involved in the process expressed a belief in their own abilities to improve their work. During the audio taped interview, this biology student stated:

> In Science 10, we did labs, and our teacher just corrected them, and you just got your mark. This year the teacher gave us the chance to

> come up with all of the criteria and the standards and that made me more aware of what I need to put in the lab. It really helped me. I think before the criteria, I might have been proficient, but now with this rubric, I realized what I had to do, so I think I am mostly strong. I know exactly what I need to do to create a strong lab.

Students were in essence given a direction for learning that required metacognition and a personal understanding. They were establishing for themselves what is was they wanted to do, why it was they were doing it and what they were trying to learn from it. I call this the "I Do For Myself" stage, where students begin to be able to demonstrate their learning, rather than a rote repetition for a mark. During the audio taped interview, this biology student described why she felt it was beneficial to include student input in the assessment process:

> I think it was because when we are involved in our own assessment we know what is expected of us. We write down the things that we are capable of. In a strong category, we write down things that we can get to. A lot of teachers have rubrics and the strong is way over your head and you know you are never going to reach that level, and that is discouraging. You feel you are always going to stay at the basic level. When we made the rubric, we made it so we can achieve that level and so that we can be happy with our work. I can get to strong by working harder. I need to work on my scientific knowledge, and read more before I actually start to do the lab. I'm starting to understand it more, because I know what is expected of me beforehand.

The statements made by this student mirrored similar comments made by the teacher interviewed at the beginning of the study. At this stage of metacognitive awareness, students were beginning to know what questions to ask of themselves as learners of science. They were finding intrinsic value in the process. They set specific goals and determined how to get there on their own. This biology student related to a particular example in her work to show how she could improve upon her reasoning skills:

> I think I should start writing out ideas that I get while I'm doing the lab, as I notice the sources of error happening. I can then keep the ideas fresh in my mind and this will help me to learn while I am doing. If questions come to mind I can write them down and this will give me

> ideas to address further in my conclusion. For example, I remember when we got a strange result in the digestion lab I wondered why at the time, and then forgot to talk about it in my conclusion.

Another biology student relates her developing awareness of the process to decreasing her frustration level. She discusses an internalization of the rubric standards in the following reflective journal entry:

> Since the first lab I have written in Biology 20, I have noticed a huge difference with information, and more importantly my comfort level in writing a lab. At the beginning of the semester I found myself confused and not certain of what exactly to put in the hypothesis, procedure and conclusion. For example, looking back on my osmosis lab I notice that my hypothesis is very vague and lacking a lot of detail. Because I didn't really know what I was doing, I ended up mistaking passive transport with active transport. Being specific in the hypothesis lets me understand the results so that I can then explain them more fully in the conclusion. By writing more and more labs, I found that identifying the variables is becoming much easier. At first I had to really think about what the controlled, manipulated and responding variables were and now those variables are implanted in my brain and I always know which ones are which.

The rubric formed part of a developmental and ongoing process that was concerned with the transference of conceptual understanding to increasingly complex and novel situations. Students were required to show rather than tell what it is they were doing, and to become aware of how they constructed their knowledge. It is this metacognitive aspect that becomes more important over time and not the rubric as an assessment tool itself. Ownership of learning at this stage is in the process of being transferred to the students. Although different students are at different stages in both their metacognitive and science skill development, the process is not intended to end at this time. It is meant to encourage student engagement throughout their high school science experiences.

Some very powerful emotions were brought out in the reflections. In some cases, doing of this form of analysis went beyond the comfort level of the students. Some suggested that they should not be expected to know what is missing from experimental write-ups and should not be required to do a teacher's job for them. For these students there was no perceived value in the peer evaluation process One student from the chemistry classroom wrote:

> This evaluation process helped me understand what labs are all about and helped me realize things that I was missing in my lab. I didn't correct the person's work very well because I was unable to find a lot of the things that were missing. I am not the teacher and I don't have high expectations for students as teachers do. I'm in chemistry to learn it not to make note how other students are doing on their labs.

This particular student was given work of a higher quality to examine in the hopes that the comparison would help her to come to a fuller understanding of critical thinking in science. She was bothered by the non-traditional role of student as expert. She had not internalised the standards of the rubric, did not consider herself an expert in the process and had gained no sense of ownership of learning. Some of the weaker students felt intimidated by the better labs and had fatalistic outlooks. They expressed concerns that the process could not possibly help them because they were unable to evaluate write-ups that they did not know how to do themselves. These students tended to use the rubrics on a superficial level. Some evaluators ignored the rubric completely and did not seem to find any ownership in it.

Many students were concerned about marking incorrectly. This tended to be a gender issue in that the girls were concerned with how the other person would feel about them as evaluators and did not want to be perceived as mean. This in turn made them less critical with their analysis. It was difficult for them to separate the work from the person that wrote it. This aspect was present in one of the self evaluations as well. A biology student found it difficult to separate how she felt about herself from her discussion of her laboratory work. For her, peer assessment and self reflection became a very personalised emotional experience. When reflecting on her work, she wrote:

> When I first began to write my pre-labs I was horrible at doing them. I didn't understand what I was doing and I had no clue

> what to write down. My observations were not correct and my conclusion was just awful.

Teacher monitoring of the process is very important, therefore, to ensure that the appropriate degree of comfort levels for these types of students are maintained throughout. Despite the use of anonymous peer assessment without set grades, all of the girls interviewed from the biology classroom expressed concern over how their fellow students might feel about them as evaluators, even though they felt they had benefited from the process themselves by being shown a sample work for comparison to their own. The boys interviewed did not share these concerns and, in fact, felt that the peer assessment was the most interesting part of the entire process. Suggestions from these students were provided for alleviating many of these problems, such as having the work assessed by groups of people rather than individuals. There is a line between a challenging assignment and one that leads students into downshifting and emotional stress. It is important that these students' voices be heard and moves be made to decrease their anxiety levels. In the future, anonymous group assessment at the initial stages may meet these gender-oriented concerns more appropriately than one-on-one anonymous peer assessment.

Summary

The data described in this chapter was collected and interpreted from the teacher interview, classroom field notes, teacher reflective journal, student work, student reflections, and student interviews, and was organized into two action research spirals. There were vast differences observed within the chemistry and biology classrooms and this affected the way in which the generalised spirals and plans of action were revised. After all of the data was gathered, the entire process was examined in light of the research questions presented in Chapter One. These questions will be subsequently examined in Chapter Five.

Chapter V: Discussion

Overview

A common problem often exists between the perceptions of students and teachers with respect to evaluation. Too often teachers give assignments to their students and wait until they begin marking them before they establish what it was they were looking for in the first place. Grades, therefore, can be perceived by students to be arbitrary when the evaluation process does not allow them to gain any personal understanding of the merits or areas lacking in their work. The basis of this thesis was to explore the benefits and difficulties experienced in classrooms where both the students and teacher are involved in developing a common ongoing formative assessment tool for developing science process skills. In this chapter I will relate the research findings to the original questions presented in the first chapter. Through an examination of the experiences of the students and myself, I will identify the positive and negative aspects encountered when using student-generated rubrics in the science classrooms researched. I will link the philosophical underpinnings of the thesis identified in my review of the literature with my interpretations of the action research. Unanswered questions brought to light by the study will be examined and suggestions for further studies will be provided.

Reflecting Upon the Research Questions

The following section will address the original research questions using reflections based on summary notes written throughout the study and insights gained in writing the conclusion. Many of the initial interpretations made during the evolution of the research spirals have been re-examined from the perspective of looking at the project as a whole rather than in isolated parts as the study progressed. Interpretations concerning the different classroom environments and the effect of context were made after the completion of the study at which point student work, student reflective journals, teacher field notes, teacher reflections, audio taped group discussions and interview data from the two time periods were compared.

Rubric Development Strategies

- What will pedagogical strategies that support the development of scientific reasoning and process skills and include students in the generation of their own assessment parameters look like? What is the best way to implement these strategies? How can an assessment rubric be effectively modified over time in response to student feedback?

During the semi-structured teacher interview the essential characteristics of rubric generation were discussed. The use of a rubric as an assessment tool can be conducive to the development of process skills that are repeatedly developed over time. According to the teacher interviewed, this formative approach to assessment has worked well in his English classrooms for long term development of written language composition skills. This view is supported by much of the literature reviewed on rubrics (Wiggins & McTighe, 1998; Andrade, 2000; and Skillings & Ferrell, 2000). Wiggins & McTighe (1998) describe the use of longitudinal rubrics as a mechanism through which "understanding develops slowly and reveals itself as a progression along a continuum for any single idea..."(p.72). The value of utilizing a set rubric for repeated classroom use in developing process skills was also demonstrated in all three of the science classrooms documented in the study. The development of science process skills in high school courses connects to the nature of science and this type of classroom coverage goes within and beyond any specific science curriculum. The use of developmental rubrics to meet these learning outcomes appeared to benefit both chemistry and biology students alike. One of the chemistry students wrote, "I really get science now. Using the rubric as a base I now know what to do no matter what lab I'm given." A similar observation was made by a biology student during the semi-structured interview when he stated, "At first it was hard, but I think I understand more about how to make up a lab. The rubric helped me to be specific in my writing so I tend to be better at it than I was before." Based on the agreement between the literature reviewed, my colleague's experiences and the data gathered in the study, it can be suggested that this type of formative assessment strategy is not limited to any one subject or even grade level.

The most effective rubrics, as suggested in the teacher interview, limit the number of criteria and have clearly defined standards of action. With a limited number of learning outcomes a rubric is much more manageable by the student. This was substantiated by a biology student when she stated in her interview:

> When we first got together to work on the rubric we all had different ideas. It wasn't until we started talking about them that we realized we only needed two or three important ones for each section. Otherwise the rubric would be too hard for anyone to get a good mark on.

After the final class rubrics had been generated, students from all three classrooms generally expressed satisfaction in their journal reflections with the clarity and number of standards chosen. This was further illustrated during the student interviews. Each of the class rubrics constructed was specific in terms of use of student language and the standards generated, although as teacher I monitored and included ideas I felt to be generally necessary for scientific inquiry. Students were reasonably happy with the class rubrics constructed and felt that their opinions were reflected in the final rubrics. One of the chemistry students wrote of the rubric, "It was pretty cool that you used our group's comments for the communication and organization section. We liked seeing our 'no fluff' idea." A unique rubric within each of the classrooms was generated using the ideas constructed by the students involved. Although general standards emerged that were similar to all three rubrics, there were distinct differences which reflected the opinions of the students. For example, only in the biology classroom was it felt that footnoted research versus plagiarism should be acknowledged within the standards. This attention to copied laboratory work among students was a wider concern in the second high school than at the first. This issue did not emerge in the chemistry classrooms and was not brought forth by these students as a necessary rubric standard. It would appear that student-generated rubrics may reflect unique classroom contexts and, as such, may be well suited to meet the specific needs of the students involved.

When providing students with a rubric template, it was suggested by the teacher interviewed that selected criteria should be constructed by the teacher and based on curriculum. After gaining an initial understanding of the meaning of these criteria, it was also felt that students should generate the standards individually before attempting group consolidation. This was to ensure that all students were at similar levels of competence and could begin the discourse with equal participation. One biology student had a similar opinion, as she stated during her interview:

> We had fun deciding upon what should go into the rubric. There was only one person who didn't really come up with any ideas and that's because he didn't put any effort into the homework. Everybody else was prepared though, so we had lots to talk about.

Teacher selection of group participants is an extremely important part of this process as group dynamics can affect the quality of the discussion. Varying the levels of abilities and motivation within the small groups appeared to be most beneficial for the weaker students. Audio taped discussions within this type of small group during the rubric consolidation process demonstrated that the differing abilities of group members facilitated a particular kind of dialogue where a stronger student clarified both the criteria and the standards for a weaker student. Equal participation during this process was not demonstrated by students who exhibited lower levels of meta-understanding. Students who were unable to articulate any concrete thoughts either verbally or in their written work, of the rubric standards, did not demonstrate any internalisation of the rubric over time in the laboratory work. As documented in chapter four, a single group containing students with mid-range abilities but a large degree of motivation showed markedly higher in-depth conversations through which the students developed shared meanings of what it meant for them to do scientific inquiry. Each student involved contributed ideas which were then discussed by the group as a whole and integrated with the ideas of others. This type of communication resulted in a clear demonstration of critical analysis and a high level of understanding of the nature of science. The act of developing the class rubric initiated metacognition. Students were involved not only in conversations about how science should be done, but also about the thinking processes involved in writing about investigative science. This was demonstrated during the student discussions that moved from the concrete aspects of the experimental design, such as the number of specific controls a write-up should have, to the nature of a control and why it is important to set up unchanging parameters of comparison during laboratory work.

Many suggestions were made by the students concerning the rubric in their reflections and during the interview process. A common concern expressed had to do with the lack of a numerical marking system. Inevitably, students wanted to be able to gauge their progress with a percentile grade. Using a rubric to assess work based on levels of quality was not typical of the previous school experiences of the students. Many students would have preferred to have had numbers assigned by the teacher for each proficiency category. This focus on summative assessment is prevalent in many science classrooms (Harlen, 1999). It is, therefore, not surprising that students' attitudes towards assessment reflect those represented by their overall school experience. Conversely, students expressed relief at not having a grade assigned to them by their peers during the peer evaluation process. In that context, it was deemed preferable to receive specific feedback based on the rubric without having any mark assigned. One biology student stated during the interview:

> When I didn't have to worry about whether the work was a 70 or 80 percent it made it a lot easier to look at each category more specifically. The person might have been proficient at communication and organization, but only basic/emerging at hypothetico-deductive reasoning.
> So after looking at each part, I then assigned the lab the category that fit the majority of the work.

Some students suggested that not all of the rubric criteria should be weighted equally when deciding on overall placement. Many felt that the science content and hypothetico-deductive reasoning criteria should account for the majority of the decision for which category an experimental write-up should be assigned. One student suggested that "high-end" and "low-end" adjectives be given in front of the categories, so that the student could know more specifically what they had to focus on in terms of improvement in their work. All of the students interviewed expressed satisfaction with the rubric generation process. It was felt that the class rubric took into account the majority of the students' ideas and had been modified appropriately through the student and teacher consolidation processes. These same students all suggested that having their opinions read in their reflections and listened to in the interview further increased their perception of having been personally involved in the rubric modification process.

Developing an Appropriate Classroom Atmosphere

- Which classroom contexts are beneficial to the development of metacognition? Do student generated rubrics work in all science classrooms and at all grade levels? How much time is required before an appropriate classroom environment of trust and respect can be developed?

Varying degrees of teacher facilitation were required during the study depending on the background knowledge, previous investigative experiences and abilities of the students. Assumptions regarding the types of students entering high school academic science courses were not always valid in relation to the reality of the classroom experience. For this pedagogical approach to benefit all levels of students, then students of differing conceptual and metacognitive abilities must be met at the level at which they are currently operating. Inadequate metacognitive knowledge restricts the degree to which individuals are empowered to control their own learning and be metacognitive (Thomas & McRobbie, 2001). In this study it was found that a shared classroom language had to be developed before students could engage in meaningful dialogue regarding their learning processes and science process skills. This development occurred quickly within the chemistry classrooms after the first open-ended experiment, but it became obvious that further classroom discussion, more specific teacher feedback and greater class time was required in the biology classroom before the students could be expected to utilise the rubric assessment criteria, develop appropriate standards and be able to meaningfully write about their thinking processes in science.

The students in the chemistry classrooms met the specific assumptions set in place prior to beginning the study. It was assumed that eleventh grade students in academic streams should have had previous experiences with abstract science reasoning and investigatory science, have attained necessary background knowledge from the pre-requisite Science 10 course and be motivated to learn about the specific area of science discipline chosen. The students in the biology classroom did not meet these standards. This class was not perceived by the researcher to contain a typical representation of students at this academic level. Many of the students had fairly poor pre-requisite grades, demonstrated little initial interest in learning biology and had not developed a sufficient degree of abstract reasoning abilities required for this level of study in biology. This presented an immense challenge to carrying out the research. The degree of teacher input and time spent on developing an adequate background in science had to be increased. Issues of discipline had to be dealt with assertively in order to establish an appropriate classroom atmosphere of trust and respect. Although the progress of these biology students was much slower, they had farther to go to reach similar background levels of understanding of the chemistry students, and thus it was not surprising that they experienced more difficulties. Some of the different strategies employed at this time to help meet the specific needs, increase motivation and accountability, and promote greater participation of the weaker biology students included providing more student time to complete and revise written work, increasing teacher feedback, facilitating group discussions by asking directional questions, assigning participation grades and monitoring student behaviour and background understanding with performance assessment during the laboratory investigations. Despite my mistaken expectations concerning the nature of the students involved, I believe that this process can be beneficial for students in the eleventh grade taking any of the academic science courses. Students gradually increased their awareness of science process skills relative to the level at which they started the course. All of the students willing to engage themselves in the process were able to establish specific goals for improving science process skills in their written work.

The development of an appropriate classroom environment required an initial two week period for the chemistry classrooms and over a month in the biology classroom. True meaningful change in this context requires not a matter of weeks, but months and even years. In a smaller school, the chances of having the same students throughout their high school years is quite high, and thus, benefits to learning can be maintained. The students that I have taught in this study will most likely be in my class next year. Awareness of the long term and transference of the knowledge gained to other classes may be more evident in smaller educational environments from both teacher and student perspectives. As one of the biology students wrote in her final reflection, "I know I can use these ideas in Biology 30 for doing labs and I'm glad I don't have to learn how to do all this stuff for the first time when I should be focusing on the Diploma exam." In larger schools, a teacher of a semesterised classroom may see the students for a short period of time only. This would make the benefits of this process for lower level students difficult.

Factors that can limit the experience include lack of motivation and perceptions surrounding the role of the teacher and student in assessment. Thomas & McRobbie (2001) examined using a metaphor for learning in chemistry classrooms and found that contextual factors were key determinants of the students' propensity to enhance their metacognition and learning processes. This was also found to be the case in this study. Students who were dissatisfied with their learning achievements and possessed sufficient motivation to be open to suggestions to improve their learning became more metacognitive over time and exercised greater control of their learning processes. Thomas & McRobbie (2001) further suggest that to enhance student metacognition, students should be given opportunities to consider the intelligibility, plausibility and fruitfulness of alternatives to their existing conceptions of learning and learning processes. Those students who expressed belief that using the rubric would help them to do better in the course over the long term demonstrated increased motivation towards the assignments. As one biology student stated during the interview, "If I can work harder at using the rubric when I write out my lab reports I know I will get better at them and my marks will get better too." Those students who had little desire to learn did not benefit greatly from the process. In order for students to engage in strategies that demand time and effort, they must be convinced of the strategies' usefulness for them. As stated by Sternberg (1998), "When students have become used to and have been rewarded over the years for passive and rather mindless learning, they will not jump at the chance to take a more thoughtful or mindful approach to what they are doing" (p.129). Gains in metacognition and learning processes may be unachievable if students hold beliefs about teaching and learning which are at odds with alternative approaches to traditional teaching strategies (Gunstone & Mitchell, 1998). The development and use of the student-generated rubric was not an effective learning tool for those students who did not see the long term benefits to themselves as learners. Weaker students often recited back those ideas they felt mirrored what the teacher wanted rather than what they actually were thinking and had difficulty transferring what they had learned to different contexts. It was important for students to believe in the value of the process itself. Commitment on the part of both the teacher and the students had to be present before any changes in the perceptions of the students were demonstrated. As one biology student wrote in his journal:

> I could do a lot better if I wanted to, but honestly I just couldn't be bothered. I don't really want to write about my work - once I hand it in, I don't really care anymore. That's the teacher's job. They know more about what is right than I do.

Students who did not feel the rubric helped them further their understanding of scientific inquiry maintained their pre-existing learning practices and did not demonstrate any marked willingness to alter their metacognition.

Contextual factors outside the classroom shape the attitudes of students and may effect the degree of willingness of students to engage in formative assessment strategies. Schools tend to be conservative regarding pedagogical change and students are often found to possess entrenched, confined and conservative conceptions of learning and lack awareness of their thought processes (Baird, 1990). As well, students typically demonstrate very transmissive views and are quick to take on passive roles in terms of learning and teaching (Thomas & McRobbie, 2001). The abdication of ownership of the learning process was evident in the less motivated students throughout the study. When focusing only on what they perceived to be what the teacher wanted, the level of student metacognitive awareness became much lower. Typically, when assignments are used constantly by teachers as a means to increase student accountability, the value of doing the assignment resides outside the learning accomplished by the student. The student thus relinquishes the work itself as well as the personal valuing of that work. The value of classroom work becomes fixed with the grade given by the teacher. This lack of personal commitment towards learning was exhibited to an extent by a few of the students in all three classrooms. These students perceived the process of constructing their assessment parameters to be a waste of time that required too much effort on their part. Ingrained beliefs regarding the teacher as expert made many students hesitant to take control of their learning.

Teachers taking on the role of creating student-generated assessment tools in the classroom must be willing to spend extra class time developing an appropriate atmosphere that promotes trust, respect and empathy. Student frustration levels must be monitored to ensure that emotions are kept at a level appropriate for learning. Factors that can lead to a negative emotional response in students include having an inadequate prerequisite understanding of the criteria for scientific inquiry, encountering novel experimental situations without set outcomes, being uncomfortable with the role of peer evaluator and being overly critical in self-evaluation as a result of self-esteem issues. If emotional downshifting in students is to be avoided then students must be presented with opportunities to reduce uncertainty and increase coping abilities (Sprenger, 1999). Within this study, the students who were perceived to be overwhelmed from the process were given extra time to complete individual assignments, assigned to groups where stronger students could help facilitate their learning and monitored carefully throughout the study. All of these students felt that expressing their concerns openly in their reflections helped to decrease their discomfort levels.

Finding Meaning Through Discussion and Reflection

- What are the benefits and difficulties experienced by students as they work collaboratively through laboratories designed to confront possible misconceptions in science? What are the effects of student dialogue, group consensus and self-reflection on this process? How does student motivation effect the internalisation process?

The experiments presented to the students were designed to bring about conceptual conflict. Open-ended, student-determined projects were undertaken and their designs were examined through group discussion using an evaluativist approach to scientific inquiry. This was done in an attempt to align the students' thinking with that of science experts. The inherent philosophy underlying the investigative approaches required by the students was based upon constructivist learning theories, which assume that when students compare their own knowledge constructions with others they can gain new insights, increase their awareness of the viability of their knowledge, and can begin the process of reconceptualising and revising their original conceptions (Vygotsky, 1986; Cleminson, 1990; Brooks & Brooks, 1993; Zahorik, 1997). Open-ended experimentation, where students developed and refined their own procedures through laboratory experience and peer discussion was a novel experience for many of the students. Concrete reasoners exhibited difficulties considering the deficiencies in their own hypotheses. Some students expressed concern with the focus on independent critical analysis in their written work. One chemistry student wrote:

> The labs were much easier to do last year. All I had to do was give back the results and use some of the terms from the textbook. I have a hard time thinking of ways to improve my lab or even coming up with a procedure. I'd rather just follow the instructions in the book.

Traditionally, closed investigations that highly specify the aim and each step of the task do not require a large degree of mental engagement. When student perceptions of traditional laboratory work are examined, there is often little evidence of students reflecting on the value of their observations and trying to link them with what they already know (Berry et al, 1999). It was found that introducing open-ended experiments that required peer collaboration increased the amount of student motivation to persist with the task. A sense of student ownership of the procedure may have lead to this increased motivation. One biology student evaluated her group's design in the following way:

> I liked working with my group members. We are really proud of our abiogenesis design. We worked hard on it and even went to my house and took pictures of each of the steps that we did, so it is really specific and easy to follow. Although we missed out on some of the important things that were mentioned in class it is easy to change our procedure to add them in. I think our group's was one of the best procedures.

It was important to introduce a degree of teacher facilitation in some cases to avoid certain groups of students giving up when encountering difficulties that could not be resolved. Allowing different groups of students opportunities to converse together and compare designs during the initial chemistry open-ended experiment also helped to increase student motivation to persist with their revisions. One chemistry student wrote about the benefit of dialogue in his reflective journal;

> I enjoyed comparing our procedure with the other groups. It made us see how smart we were. We changed a few things after looking at their experiments but mostly we had some really good ideas that they wanted to try.

Westbrook (1996) examined whether notions students hold about scientific concepts are impacted by generating and testing hypotheses in three ninth grade physical science classes. In her study, she questioned whether or not a concrete operational learner who has difficulties with metacognition can come to any meaningful conceptual change if didactic pedagogies are employed. As well, she maintained that larger degrees of student autonomy and self-reflection should be incorporated into conceptual change dialogues (1996). Within this action research study, it was found that group discussion and comparison of student work of varying quality increased the degree to which students challenged their own initial conceptions. Misconceptions were inherent in several of the abstract science concepts encountered through experimentation in both the chemistry and biology classrooms. During the open-ended experiments students compared their designs with that of others. Evidence that some students were able to distinguish between results that were gained through faulty experimental controls from that of results which agreed with fundamental scientific hypotheses were found in each of the three classrooms. Peer group conversations appeared to have had a large impact on the ability of students to revise their work to meet that of acknowledged science experts. Many students reported in their reflections that it was through examining and discussing the work of others that they were able to come to deeper understandings of the merits and problems within their own work. Teacher examination of the specific revisions that students made within their work after group discussion demonstrated a large amount of agreement with the student perceptions documented in their reflective journals.

The experiments chosen for the students were designed to progressively increase in their degree of complexity. Prior knowledge concerning scientific inquiry gained from the initial open-ended experiment was reinforced in subsequent laboratory experiences, but the aim was to increase the degree of process skill rehearsal rather than repetition (Lowery, 1998). The ability to critically analyse results obtained through experimentation was not always transferred by the students to new situations when they were required to perform peer evaluations. For example, students in the biology classroom that had been able to revise their constructed knowledge concerning abiogenesis during a group discussion were not necessarily able to critically examine incorrect descriptions about osmosis during the individual peer evaluation process. Although some students demonstrated abilities to independently revise their work and that of their peers, not all students were proficient at this by the time they were asked to individually peer evaluate the second experimental write-up. In light of the observed advantages gained through student dialogue, it would perhaps be more beneficial to introduce the peer evaluation process with small group discussions and collaboration rather than individual peer assessment. Having groups of students assess anonymous student work using the rubric may increase the chances of acknowledging misconceptions and help to bring this awareness to a larger number of students.

Gunstone (1998) suggests that science education is lacking when students do not understand that scientific ideas are enhanced through a process of sharing, debating and consensus building. There was evidence in the audio taped group discussions during the rubric consolidation process that students imparted knowledge to one another and in turn came to a deeper understanding of the necessary standards for the development of science process skills. Familiarity and an understanding of scientific inquiry appeared to be fundamental for students to be able to independently identify standards of quality. The internalisation of standards of quality for science process skills was already in place for those students working at a higher level of understanding. Weaker students who were willing to engage themselves in the process appeared to benefit the most once they began to analyse their work in a more specific way. Over time, when the standards were related to on an ongoing basis, students began moving from vague descriptions of their work to a more specific analysis. By relating to the rubric, these students began to express more specific thoughts about the nature of scientific inquiry and its relevance to their laboratory work. This chemistry student wrote about one of her laboratory conclusions:

> I can see why it's important to think about how your results might be disproving your hypothesis. So when we couldn't break down water by heating but we could by electrolysis, it made sense to classify it as a compound instead of an element, which disagreed with our initial statements about heat. I never thought about labs that way before, but now I understand the purpose of writing out the hypothesis in detail, so you can go back to it later and think about whether the initial theory is still true.

When students were given models of varying quality to compare they began to gain a sense of the necessary elements for demonstrating quality work. The process of generating a rubric through experience, discussion and collaboration served as a metacognitive platform that helped move students toward greater ownership of learning. Increasing the degree of teacher feedback, class discussion time and personal reflection helped such students move towards a more personal understanding of what it meant to think and write about experimental science.

Teacher and Student Perceptions

- Do the perceptions of students concerning self and peer assessment agree with the perceptions of the teacher? Does increased metacognition and internalisation of the rubric standards have an effect on this agreement or disagreement?

With the incorporation of self and peer evaluations and written reflective journals, the rubric became more of a metacognitive vehicle than an assessment strategy over time. The idea that laboratory work is a thinking task and not just "hands on" work was evident in this student's chemistry reflection:

> I make sure that I am really prepared for labs now. I didn't used to even read the labs before I did them in class. But now I want to understand it beforehand because I'm going to need to talk about the stuff that happens in the conclusion. If I don't write stuff down as I go I might miss something when I come back to it later. So I think a lot more about what I am doing and what is happening in the lab as I go.

For this student, the process helped to build a different framework for her thinking. Laboratory work involved interaction with ideas and not just equipment.

In order for students to progress towards an internalisation of the rubric standards and a deeper understanding of themselves as learners of science they had to be actively engaged and affectively involved. During the study, many students expressed a strong sense of their own involvement. One of the biology students pointed to the rubric during his interview and stated:

> I feel that this is my work. It belongs to me because I helped write it. It's not just something you gave out in class to mark us with that I would never look at.

A similar sense of student autonomy was also evident in many of the student reflective journal entries. One chemistry student wrote:

> I'm kind of sick of rubrics because all of our teachers give them out to us. This is the first one that I got to make though, and so I think this one is kind of special. It is our rubric, not the teacher's. We get to decide what's important and what's not.

Regardless of the level of ability, those students who began to see value in the process used the rubric to give them a clear perception of what they needed to do to be able to obtain a higher degree of proficiency in their work. Some students became increasingly metacognitive and discussed evidence of revision of their learning processes. Other students reported little or no progress. Less motivated students demonstrated a lack of effort and the quality of their work showed little progression over time.

No clear agreement existed between the perceptions of the teacher and the students in terms of the quality of their own work. The degree of perceived change in each student was individual and it is important to acknowledge that no single teaching strategy will result in the same outcomes for each student. Academically strong students already working at a high level of competence and understanding in science did not benefit greatly from the process. In general, the stronger students from all three classrooms were able to identify peer work using the rubric along the same categories of proficiency as I did when I examined the work from the perspective of an experienced teacher. These same students handed in work of high caliber, were able to critically analyse their own work and look for areas of improvement. Most of the higher ability students did not feel they benefited greatly from evaluating lesser quality work. One of the chemistry students wrote in her reflective journal:

> I didn't really like marking the lab I got. The person didn't put any effort into it so felt I was basically redoing it for them. I wish I had gotten a better lab to look at because then I would have been able to find more stuff that I had forgotten in my own lab. That way I could improve more.

Academically weaker students appeared to benefit the most through peer discussions and modeled work of quality. Those lower to mid-range ability students that willingly engaged themselves demonstrated marked improvements in the quality of their work over time. When students compared the work of others they developed a better sense of their own work. The evaluation process allowed students to have a better understanding of the standards of quality defined by the rubric and this, in turn, allowed them to analyse their work in a much more specific manner which was relatively consistent with that of the teacher's perceptions. Less motivated students appeared to have benefited the least from the process. These students were much more willing to abdicate ownership to the teacher during the rubric formation process. Students who were unsure of themselves often assessed their work on a much lower basis than I did as their teacher. Less motivated students often focused on the superficial elements of the write-up and did not relate to the rubric standards when deciding upon their own placements or the placement of others. Weaker students were the least likely to be able to identify incorrectly used terminology and often missed discrepancies between the results and their scientific explanations. It can be difficult to tell the difference between a student who does not understand the process and a student who simply does not care. If one is unwilling or unable to enter into a discourse concerning how one learns, then a process such as this becomes an assignment done for a mark, rather than for personal growth.

Many of the students from the chemistry classrooms had me as their teacher in either their previous Science 10 or Biology 20 classes. These particular students had more previous experiences with doing and writing about science experiments and many students were at a level of excellence prior to beginning the study. For these students, the rubric generation process has been somewhat redundant. This prior experience with how I had evaluated their work in the past may have been prevalent in some of the students' minds as they generated the rubric standards. This might have been problematic in that it could have set up a degree of teacher control that may have interfered with genuine student responses. If a rubric is to be completely student-generated, then the process might be better begun in tenth grade science. The correct balance between authentic student input and teacher influence is something that needs to be explored more deeply. A rubric that mirrors what teachers think does not create student ownership or internalization of the evaluation process. The question arises as to how to design this process so that the experienced students have a chance to be challenged to a larger extent.

A Metaphor of Ownership

A metaphor may be used as a method of understanding something that would otherwise not be understood. It is a way of reaching personal understanding and meaning by using the familiar to help lead to the unfamiliar. I have chosen ownership as a metaphor for the pedagogical philosophy inherent in the research and the changes that occurred in both myself as teacher and my students as learners. The somewhat existential philosophy behind which my research is based centers around the metaphor of ownership in the context of learning. Existentialism explores the individual existence, whereby the individual must assume responsibility for his or her acts of free will. When one has ownership of something it can be said to be within his or her possession. As such it belongs to the individual. Science is often taught as a series of objective facts to be memorized and recipe book experiments to be performed. When science educators value content over conceptual understandings, they are setting up a system whereby the power and ownership of learning stays in the hands of the teacher. If students begin to ask their own questions and construct their own understandings of reality and knowledge, ownership can be transferred back to the learner. Teachers do not own children and yet the entire school system is set up to keep the ownership and control of learning in the hands of the teachers. By giving and valuing multiple choice questions, educators are modeling a world where there is only one right answer and that answer can only be found through the teacher. This action research study explored the possibilities inherent in an environment that challenges students to take responsibility for their own learning and to begin to transfer the ownership of learning from the teacher to the student. It described the journey begun by students with a "do for me" mentality and documented their progressions towards an "I do for myself" state of metacognitive awareness. It was not an easy process. It required an affective emotional commitment on the part of the participants.

For myself, as both researcher and teacher, the sphere of the possible has been widened by this study. Through listening to the discussions of my students, reading honest student reflections and having in-depth conversations with students about science, I have come to a greater understanding of the power of ownership of learning. I recognize more fully some of the problems inherent in the effective implementation of the process, but still believe in its potential. When examined as a whole, I began to see an overlying spiral that encompassed both the smaller spirals of science and metacognitive development. This super structure at work involved an increased awareness of the participants of the underlying purpose. To reach this awareness involved coming to a more personal understanding and a deeper clarification of what was being done to my students as learners and myself as teacher as we became engaged on different levels. Classroom experiences have made it easy for students and teachers to become cynical with education and the learning process. But if one is willing to do more than go through the motions of learning, to give a full commitment and to affectively involve oneself in the process, then the value for the long term becomes apparent. As one of the biology students described during the interview:

> At first this was just a lot of extra work for me and I thought it was a big waste of time. But after the first few labs, I realized that what I was doing for one lab, like looking for variables, controls and sources of error, I could do for other ones. It has also helped for the exam questions that get you to look at results from experiments. Those questions used to freak me out and I had no clue how to do them. But now I think they are a lot easier to do. If you know how to do one lab, you kind of get how they all work.

This is not about the moment. It is about gaining an understanding for future benefit. When the participants of the process become engaged at this level, it is truly a powerful and worthwhile experience.

Unanswered Questions and Future Studies

This action research study was designed to document changes within three science classrooms as the students and I moved towards developing and using a common assessment tool for science process skills. Many different factors were at play during the study and the divergent ecologies of the classrooms helped to demonstrate that what appeared to benefit the students from one classroom did not necessarily benefit the students in another classroom. Many teacher and student concerns arose that gave rise to questions that were not addressed within the study. A discussion of potential questions and their implication for future studies follows.

If student-generated rubrics can be used to help develop science process skills and increase student awareness of the nature of science, at what age level should these formative assessment strategies be initiated? How can metacognition be developed in younger science students? Because the development of science process skills is important in all science classrooms, perhaps this pedagogical approach would have greater long term benefits if initiated at younger grade levels. The biology students differed greatly from the chemistry students in terms of their previous experiences with experimental science. Those chemistry students operating at a high level of understanding did not benefit greatly from the process, while biology students lacking in basic science understandings required much more time and teacher facilitation. Introducing these pedagogical strategies at a younger grade may lead to greater long term improvements in hypothetico-deductive reasoning abilities and allow educators more time to incorporate class discussion and collaboration. Abstract thinking is developmental and progresses over time at different age levels for different children (Fischer & Rose, 1998). Would younger students be less able to identify the necessary standards inherent in an evaluativist approach to scientific inquiry? To what extent would teacher facilitation be required at earlier grades?

Would students exhibit greater benefits if there were increased agreement between science educators in terms of how to construct experimental write-ups within an evaluativist framework? There is a great discrepancy between how experimental science is taught by science teachers (Zohar, 1998). Without a common framework of scientific inquiry, student are often being asked to construct different laboratory design formats between one science classroom and the next, as well as between different grade levels. Students tend to design their work to fit the requirements of the teachers and often do not transfer what they have learned from one class to the next. As one chemistry student wrote in his reflective journal, "It is really annoying to have to change the way I do my lab write-up for every different science teacher I get." If the science students were asked to build their own science process assessment tool in Science 10 and then use this same rubric with modification over time throughout their eleventh and twelfth grade chemistry, physics, biology and general science courses, it would be interesting to track their progress over this extended time period. Small school environments often have the same teacher teaching the same students throughout their high school courses, so the feasibility of this type of study would have to be based on teacher cooperation and smaller schools. Would long term use of this pedagogical strategy benefit students in terms of their ability to critically analyse scientific data and transfer their understandings to other contexts?

How can formative assessment strategies focusing on long term skill development be promoted within the context of an educational environment that values summative evaluation and standardized testing? Incoming attitudes of students affect their willingness to respond to classroom pedagogical approaches that go beyond the status quo. Both teachers and students need to begin to recognize the long term value of formative assessment strategies that put less stress on getting content right and more focus on developing and improving upon important learning skills that can be applied to novel situations (Harlen, 1999). Wiggins and McTighe suggest that curriculum should be approached by looking at the big picture and that educators should begin with key design questions, set intelligent priorities, self-assess and critique the elements of the design against appropriate criteria and progress towards products that meet the design standards in light of the achievement target (Wiggins and McTighe, 1998). They further describe a multifaceted view of understanding as one that incorporates an ability to explain, interpret, apply, have perspective, demonstrate empathy and reveal self-knowledge (Wiggins & McTighe, 1998). Would the degree of student motivation and internalisation of the learning process be increased if educational environments began to value a similar approach to understanding?

Are gender differences influencing the extent of student cooperation and involvement? During the study, female students tended to be more accepting of the entire process than were male students. Organizational skills, listening skills and the ability to work in groups was generally less valued by the male students. Despite this, all of the males interviewed in the biology classroom stated that they enjoyed the peer evaluation process, while the females expressed concern with how they might be judged by their peers. Although both male and female students having weaker conceptual understandings in science and less experiences in scientific inquiry demonstrated the most frustration and the least motivation towards the process, only female students expressed emotional responses to the process in their journal reflections. Females students often doubted their role as expert evaluator. The action research study did not collect data specifically on the basis of gender, nor were questions of gender asked during the interviews. Do formative assessment strategies that involve comparison of peer work promote greater negative emotional responses in female students? Would working in small evaluation groups rather than one-on-one peer evaluations alleviate some of the concerns expressed by the female students in this study?

Was my role as researcher compromised by participation in the study? I maintained a dual role as both researcher and teacher throughout the research process. How did this active participation influence my interpretations? Because the study took place over 24 months, more data was collected than used. The layering of data was especially important in this situation to ensure that my perspective was not dominating its interpretation. I came to the research with a set of values and steps had to be taken in gathering the data to ensure that my interpretations were not overly influenced by my assumptions. Many of these assumptions had to be acknowledged and revised. In order to begin subsequent stages of the research, data had to be continually gathered and interpreted. This was difficult to do when acting as both full time teacher and researcher. Feedback to students had to be meaningful, but also timely. The time commitment on my part was immense. Was the selection of interview quotes and student reflection work influenced by my commitment to changing my assessment techniques to involve students and increase their sense of ownership?

Conclusion

Although the pedagogical approach used in this study may be easier to initiate in some classroom contexts more than others, it still has value across science disciplines and for various levels of students. I have found that classroom context is an important component of a student's ability to be aware of understanding how they learn. Students need to be met at the level at which they are currently operating. In this research situation, that has meant that the first spirals took longer than expected. More teacher input into the clarification of the science was required and some students were unable to affectively engage themselves in the process. As with most secondary high school classes, the issue of motivation is important to obtaining meaningful student responses. The greater the degree of teacher intervention the less chance of true student internalisation. Students need to become aware of the long term benefits of the process beyond the marking of the next laboratory write-up. One of the factors that may make this difficult is the way students have experienced education over time. When teachers encourage students to take notes and give multiple choice tests, students are not being actively engaged in learning. With our current focus on marks rather than learning by administrators, educators and parents, it is no wonder that intrinsically derived desires for learning a subject area are being lost in the struggle for increased accountability. Assignments which challenge students to step out of the overlying pattern in which their school experience is based require effort and a willingness to participate for reasons other than a mark. If the students see this process as something that they are being made to do, then the results become difficult to interpret. The more our educational system focuses on exam results rather than learning accomplishments, then the more difficult it is to encourage students to look to themselves rather than their teachers for learning. In the context of this kind of educational environment, it is no wonder that our students come to our classes with a "do for me" mentality.

The philosophy behind authentic assessment and learning needs to be promoted between the different science disciplines as well as other subject areas and across grade levels. This requires a broader outlook than any one teacher can accomplish. Students who are required to design their own procedures, carry out experiments with unknown outcomes and critically analyse their findings on a deeper level are experiencing a different way of doing science than by following instructions from a textbook. The authentic science process should be ongoing as skills develop more fully when the student matures cognitively and emotionally. With a fuller understanding of the issues behind the nature of science and the use of technology, our students can begin to make informed decisions. They can begin to question the type of information that is being presented to them through the media. A population driven by scientific and technological issues that does not understand the underlying processes involved is easily manipulated (Berry, 1986). It is up to our educators to make attempts to integrate these ideas across not only the science curriculum, but also between subject areas. If students go from one science classroom to the next with different teacher expectations, the insights gained from this pedagogical approach may be limited. A dissected view is not a complete one and may do more harm than good, as it tends to reinforce the prevalent world view on technology rather than to evaluate it (Brouwer, 1992). Students need to be able to understand the methods for which science derives the evidence for scientific claims. Our current science curriculum retains its past emphasis on presenting science as value-free objective knowledge. It has become a succession of facts to be learned without any overarching coherence or contextual relevance to future needs (Selby, 2000). Our methods of incorporating scientific experiments into the classroom reinforce this ideology. When authentic science and appropriate assessment tools are in place within our science classrooms, it is my hope that students will begin to internalize deeper understandings of how science is performed and currently evaluated in our society. The ability to critically analyse the way scientific information is presented is an area science educators must begin focusing on if we wish our students to make informed decisions in our industry-dominated society.

When a student-generated rubric process is limited to a set number of criteria and uses clear standards depicting action, it can be a vehicle for helping motivated students to internalise standards of quality and allows them to become more aware of themselves as learners. Traditionally, science teachers do not include this type of metacognitive student input in assessment. Self-reflection and metacognitive skill development can help educators facilitate an educational experience that allows students to think for themselves. When students believe that their constructions of knowledge are valued in the classroom and that knowledge is not something to be doled out by the teacher, then the level at which classroom science is understood and applied can be much more meaningful.

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Thesis Appendices

Appendix A: Faculty of Education Research Ethics Committee Review

FACULTIES OF EDUCATION AND EXTENSION RESEARCH ETHICS BOARD

Graduate Student Application for Ethics Review

Name Jennifer MacLean **Student ID** 0170620

E-mail: jenmaclean@compusmart.ab.ca

Project Title: Exploring Metacognition, Student-Generated Rubrics, and the Development of Scientific Reasoning and Process Skills in a Science Classroom.

Project Deadlines:

Starting date February 5, 2002 **Ending date** June 15, 2003

If your project goes beyond the ending date, you must contact the REB in writing for an extension.

Status:

___ **Master's Project** ✓ **Master's Thesis** ___ **Doctoral Thesis** ✓ **Other** EDSE 607, Coursework **(Specify)**

The applicant agrees to notify the Research Ethics Board in writing of any changes in research design after the application has been approved.

Olenka Bilash

Signature of Applicant

February 28 ~~19~~ 2002

Date

The supervisor of the study or course instructor approves submission of this application to the Research Ethics Board.

Jennifer MacLean

Signature of Supervisor/Instructor

February 28 ~~19~~ 2002

Date

ETHICS REVIEW STATUS

✓ Application not approved

___ Expedited review approved by Unit Statutory member/Alternate

___ Review approved by Research Ethics Board

Norma Nocente

Signature of REB Member

March 7 ~~19~~ 2002

Date

Appendix B: Sample Teacher Interview/Discussion Questions

1. What are some of the benefits and disadvantages of using rubrics as an assessment tool?

2. What are some of the benefits and disadvantages of using student-generated rubrics as an assessment tool?

3. In what ways do student-generated rubrics differ from teacher-generated rubrics?

4. What are some ways that student-generated rubrics can be effectively incorporated into a classroom? How can an environment of trust be best developed to allow for equal student voice, respect among peers and true collaboration?

5. How important are student reflective learning logs in the assessment for understanding process?

6. How can student frustration with novel situations and peer assessment be decreased?

7. Explain some of your views about assessment practices. What are some common teaching philosophies amongst secondary school teachers? Are these ideas interdisciplinary? Why or why not?

Appendix C: Sample Biology 20 Student Interview Questions

1. Do you believe the class generated rubric was helpful in assessing laboratory work? Why or why not?

2. How would you change this rubric?

3. Please indicate some positive and negative aspects about the rubric development process.

4. Did having a say in the rubric criteria allow you to better understand and assess your own work? Why or why not? In what ways specifically?

5. Did the group evaluation process help you understand how to do science and write about the scientific method? If so, in which ways? If not, why not?

6. Do you feel better able to apply what you know to a different lab? Why or why not?

7. Of what value are the metacognitive journals?

8. Please indicate some positive and negative aspects about doing the journals.

9. In your opinion what is the reason for involving students in the assessment process?

10. How do you feel about peer group and individual assessment of lab work?

11. Please indicate some positive and negative aspects about the group assessment process.

12. How do you feel about self-assessment of lab work?

Appendix D: Chemistry 20 and Biology 20 Planned Classroom Action

Chemistry 20 **(February-May, 2001)**	**Biology 20** **(February-May, 2002)**
1. Introduction to Scientific Inquiry with an Open-ended Investigation: Law of Conservation of Mass -Students in small groups were required to design a specific procedure for testing the Law, choosing from three different reactions for their design. -Many alternate procedures were attempted and documented. Changes were made accordingly to create optimum conditions for a closed environment -Data was graphically represented, and students individually wrote their first laboratory write-ups, which included a conclusion that addressed an analysis of the results as well as possible sources of error arising from their experimental design. -Groups performing the same experimental reactions compared their results and determined through discussion which design was the most effective. -Misconceptions regarding the loss or gain of mass in chemical reactions were peer-addressed.	**1. Introduction to Scientific Inquiry with an Open-ended Investigation:** Disproving the Theory of Abiogenesis with a Thought Experiment -Students in small groups were required to design a specific procedure for disproving Aristotle's Theory using cheese and the growth of mold. -Each group was required to present their experimental designs, data and conclusions to the class. -Through large class discussion, the most effective designs were determined as those which accounted for both a control, a sterilization process and a vacuum. -Students wrote an initial laboratory write-up, which included a conclusion that addressed abiogenesis and possible sources of error arising from their experimental design. -Misconceptions regarding the Cell Theory and the creation of life were addressed through initial discussion and later peer and self assessment.

2. Generation of the Class Rubric for Science Process Skills: -Initial classroom discussion of what a rubric is and how it functions as an assessment tool. Definitions of what is important in scientific inquiry were discussed as a class based on the previous investigative experience. -Students were given an initial rubric template with five teacher-set learning outcomes for science process skill development: scientific methodology, scientific content, presentation of data, hypothetico-deductive reasoning and communication and organization. Students were asked to write down a set of standards for each of the following categories of quality: strong, proficient, basic/emerging and weak/incomplete. -In groups of three and four, students were asked to consolidate their criteria of quality and create a group revised rubric based on discussion and mandatory consensus. -The core information from each of the compiled group rubrics were extracted and incorporated into the finished class-created rubric.	**2. Generation of the Class Rubric for Science Process Skills:** -The same basic plan of action occurring in the Chemistry 20 classroom for generating a classroom rubric was in use for the Biology 20 classroom. Two of the Biology 20 small group discussions were audio taped and transcribed for subsequent analysis.

3. Rehearsal and Application of Science Process Skills Towards a Novel Situation: Element and Compound Identification	**3. Rehearsal and Application of Science Process Skills Towards a Novel Situation:** Osmosis and Identification of Solution Tonicity
-This experiment was specifically set up to address the difficulties of procedural generalizations, open systems and subsequent loss of products, assumptions in qualitative measurements and the limitations of using heat to break chemical bonds. The critical evaluativist approach to scientific inquiry developed in the first investigation was further applied in a progressively more abstract context. -Students worked in the same established laboratory groups to complete the investigation. They individually submitted write-ups using the class rubric as a guideline. These were anonymously distributed for peer assessment. Students were graded on their critical assessment of the laboratory they were given to mark and their use of the rubric. -Students were also asked to self-assess their work according to the rubric and reflect upon the evaluation process and the rubric itself. -The work was teacher-assessed and compared with the two student evaluations.	-This experiment was set up for performance assessment. Students were required to develop a procedure for determining whether or not a solution was hypertonic, isotonic or hypertonic based on observed changes in the shape of onion cells. Osmosis is an abstract concept involving a description of the diffusion of water through a semi-permeable membrane. This is often a counter-intuitive concept, with students often mixing up the movement of solute with solvent. The critical evaluativist approach to scientific inquiry developed in the first investigation was further applied in a progressively more abstract context. -The same basic plan of action occurring in the Chemistry 20 classroom for peer and self assessment of this second investigation was in use for the Biology 20 classroom.

4. Student Metacognition and Reflection on an Accumulation of Their Investigative Work over Time: -Students performed a number of subsequent laboratory investigations, including a performance assessment involving qualitative methods of identifying compounds in solutions and comparing quantitative designs for stoichiometric calculations. -Students were asked to accumulate their investigative written work over time in a duotang. At this point, students were encouraged to look for patterns of strengths and weaknesses in their work, according to the class rubric. The intent of the student learning log was to give students the chance to voice their opinions and reflect on the assignments as a whole. Students were asked to write about their critical analysis skills and comment on areas that needed improvement. The journal process was meant to promote metacognition and a sense of awareness of the quality of work being performed.	**4. Student Metacognition and Reflection on an Accumulation of Their Investigative Work over Time:** -Students performed a number of subsequent laboratory investigations, including a performance assessment involving the identification of food types, and a comparison of the factors that effect enzymatic reactions. -The same basic plan of action occurring in the Chemistry 20 classroom for development of student metacognition and reflection through learning logs was in use for the Biology 20 classroom. -Six students were interviewed at this time to provide more in-depth feedback concerning the weaknesses and strengths of the rubric, possible ways in which the rubric could be improved, how they felt about evaluating themselves and others, and whether or not they felt they were benefiting from the process.

Appendix E: Rubric Template for Science Process Skill Evaluation

Assessment Criteria:	Strong	Proficient	Basic/ Emerging	Weak/ Incomplete
Scientific Methodology				
Scientific Content				
Presentation of Data				
Hypothetico-Deductive Reasoning				
Communication and Organization				

Appendix F: Student Peer Assessment and Metacognitive Reflection Assignment for Biology 20

Peer Assessment Assignment

Each student is assigned an **osmosis lab write-up** to evaluate. Secret names are used to ensure anonymity. Scientific inquiry involves the ability to analyze data and to look for meaning. You will be graded on your ability to critically analyze the work using the class-designed rubric. Do not write on the lab itself. Place your comments on a separate piece of paper. Be sure to include your name as marker, and the secret code name of the person whose work is evaluated. Place this into a separate duotang for your Biology 20 lab work.

1. **Evaluate** the work by specifically examining **each of the 5 main criteria** separately (scientific methodology, scientific content, presentation of data, hypothetico-deductive reasoning and communication and organization). For each of the criteria, decide **where the work is best categorized** (strong, proficient, basic/emerging and weak/incomplete) and **explain why** by relating to specific points on the rubric.

2. Give the work an **overall placement** (strong, proficient, basic/emerging or weak/incomplete) and **give specific reasons** for your decision. Do not give the work a numerical rating.

3. Provide **feedback** to the individual that has done the write-up. Comment specifically on the areas that were **done well** and provide specific **suggestions for improvements.** Please provide honest feedback that evaluates the work, and not the individual in any way. You will be marked on your analytical skills, and will be docked marks for any inappropriate comments.

Journal Reflection:

Based on your initial use of the rubric, comment on its validity by addressing the following questions. Your comments will be used to modify the rubric to ensure that it meets the needs of our class lab work. Date this reflection and include it on a separate sheet of paper in your lab duotang.

1. What was the most useful part or parts of the rubric? Why?

2. Which part of the rubric did not work well? Why? How should it be changed specifically?

3. Did assessing a sample student lab help you to understand which areas in your own work need improvement and which areas you excel in? Specify these areas.

4. Assess your own work using the rubric and explain why you have categorized yourself within each of the given criteria.